Sabkha Soil Improvement Utilizing Stone Columns: A Case Study

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Abstract

This paper discusses the ground improvement using stone columns for the construction of a new lattice communication tower in a gas plant in Saudi Arabia's Eastern Province. The geotechnical investigation data collected at the project site revealed subsurface conditions of loose to very loose sabkha soil with low SPT and N values (< 4) between 2.7 m and 13 m depth. Depending on the design requirements, ground improvements must be considered under the foundation of lattice towers to operate reliably and safely. The study discusses geotechnical investigations, stone column construction methods, and verification or confirmation tests used to ensure the project's successful execution. The outcomes of this study indicate that stone columns can be utilized efficiently to enhance bearing capacity and reduce settlement beneath foundations constructed on sabkha soils.

Keywords: Sabkha, Ground improvements, stone columns, SPT, bearing capacity, settlement;

1. Introduction

Lattice towers have long been recognized as structures that provide communities with a variety of civil services, such as television, radio, and power line transmission. This structure has several advantages, including design simplicity, ease of construction and wind resistance. Construction costs and erection time are significantly lower when compared to other approaches, such as solid reinforced concrete structures. It is desirable for those towers to be distributed to effectively perform their functions. In several cases, lattice towers need to be erected in severe soil conditions, such as sabkha areas. Construction had previously been prohibited in areas with such deposits due to their geotechnical hazard. However, due to the scarcity of land in urban areas, development is occasionally extended to regions having weak strata.

The name "sabkha" is derived from an Arabic word that describes saline flats that are underlain by sand, silt, or clay and are often encrusted with salt [1]. It exists in flat places and contains a lot of salt because to the evaporation of its moisture content. This type of soil can be found in abundance throughout Saudi Arabia, particularly along the country's coastlines. The spread of sabkha soil in the Kingdom of Saudi Arabia is depicted in Figure 1 [1]. The variety of material components as it is composed of several layers of soil, as well as salt sensitivity to water contact, are typical characteristics of sabkha soil, resulting in excessive differential settlement and a reduction in bearing capacity [1]–[4]. As a sequence, sabkha has a significant collapse potential, mostly because of the dissolving of salt caused by the absorption of water. Collapse can also occur as a result of the leaching of calcium ions from the soil and the modification of the soil grain as a result of loading [2]. As a result, constructing on sabkha soil demands the design of deep foundations to pass through the weak strata, which is both expensive and time demanding. Another acceptable technique for enhancing bearing capacity and avoiding settlement is ground improvement utilizing stone columns.

Stone columns have been frequently employed as a low-cost, quick, and environmentally friendly technique of ground improvement. The approach is widely employed to improve the bearing capacity of weak soil, specifically those beneath large raft foundations and embankments. The procedure entails partially replacing loose and/or soft soil with cylindrical columns made of granular material that have been compressed to the necessary density. The granular fill is composed of a stone/gravel or stone sand mixture in the proper proportions to fill the void. When a structure is constructed over a region treatment by stone columns, most of the pressure is transferred to the stone column due to the higher stiffness of the stone column compared to the adjacent weak soils.

Due to the improved drainage effect provided by stone columns, consolidation time and compressibility are reduced, while load-bearing capacity and shear strength are increased [5]–[7]. This mechanism differs from rigid piles, which pass through soft ground and transfer stress to the stable layers [8]. In contrast to native soft soil alone, the presence of the stone column results in a composite material that has lower compressibility and higher shear strength [4]. Stone columns gain their resistance from bulging, which causes passive pressure to form in the surrounding soil because of the bulging [5].

The Vibro- replacement and Vibro- compaction technologies are the most employed for stone column installation. Improved cohesionless soils are often achieved via the use of the vibro-compaction method, whereas cohesive and cohesionless soils are improved through the use of the vibro-replacement method [9]. The equipment consists primarily of a vibrator that is elastically suspended from extension tubes equipped with air or water jetting systems and is supported by a crane or base machine. In addition, the system incorporates provision for stone delivery, control, and verification devices. The performance of a densification system is influenced by the properties of the machine. Size, frequency, amplitude, and eccentric force are all important parameters. Because each of them is unique to a certain soil, a field trial is essential to explore the optimal values for maximum densification [4], [10].

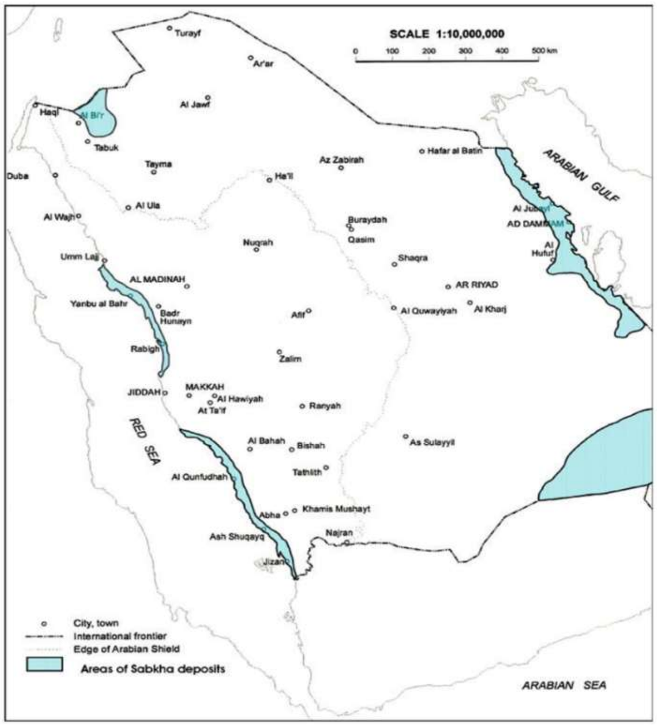

Figure 1: The Approximate Distribution of Sabkha Soil in Saudi Arabia [1].

In the case of sabkha soils, the Vibro-replacement procedure is typically used to install stone columns. During this process, the vibrator displaces soil radially and flushes out the weak soil, resulting in the formation of a cylindrical compact zone [11]. According to the condition of the subsoil, the degree of densification necessary, the equipment specifications, and the construction technique used, the Vibro-replacement stone columns are often placed in a square or triangular grid pattern at a spacing of 1.5 m to 4.0 m [12]. Because of the soil extraction produced by water jetting, the diameter of a stone column constructed using the wet approach is often larger than that constructed using the dry method. According to Raju (2004), the wet process has a higher production rate when compared to the dry process and has the capability of treating grounds to depths of approximately thirty meters [13]. Stones with grain sizes ranging from 35 mm to 75 mm can be used in the wet process, whereas the dry method requires stones with grain sizes ranging from 15 mm to 35 mm (17 -19).

This paper describes the experience of building a 90-meter-high lattice communications tower in sabkhah soil, including soil conditions and design considerations for stone columns, installations, descriptions of constructional phases, and verification or confirmation tests.

2. Project Description

The case study data was gathered from the project of the construction of a new radio communication tower at a gas plant in the Eastern Province of Saudi Arabia. Radio communications are a crucial tool that plant staff use for day-to-day tasks as well as emergency response actions. Regionally, the gas plant is located within the sabkha deposit areas, and it is built on a wide backfill sand layer on top of sabkha soil.

3. Subsoil Condition

The project site is in an area of coastal Aeolian dunes. This region is characterized by sand deposits combined with silt and/or clay that are in a loose state, which is referred to as "Inland Sabkha." A soil investigation program has been carried out at the Tower site. Three boreholes were drilled at the project site to a depth of approximately 45 m. A total of two (2) PCPT (Piezocone Penetration Test) tests have also been performed on the site. The cone penetration tests began at ground level and continued to the end of the PCPT depth. The depths that were achieved ranged from 18.5 to 17.5 meters.

Subsurface stratigraphy and design parameters are evaluated up to the maximum drilling depth using field exploration and laboratory testing of representative soil samples. Figure 2 shows a summary of SPT, N values, PCPT test, and the subsurface strata encountered in boreholes. The stratigraphy observed from borings generally indicates the presence of a top 3 m loose to medium dense sand with a silt layer, followed by very soft, compressible strata (Sabkha) up to 13 m depth. The density of the strata beneath the sabkha layer ranges from medium to very dense layers, and this condition continues to the maximum depth of investigation. The ground water level was checked in all the boreholes 48 hours after finishing the drilling of each borehole. In this investigation natural ground water table was 2.7 m from ground surface encountered in all boreholes. It was discovered that the drilling profiles were varied in each borehole. This is one of the sabkha characteristics, which are changes in physical and chemical properties that occur vertically and horizontally over a short distance [1], [14].

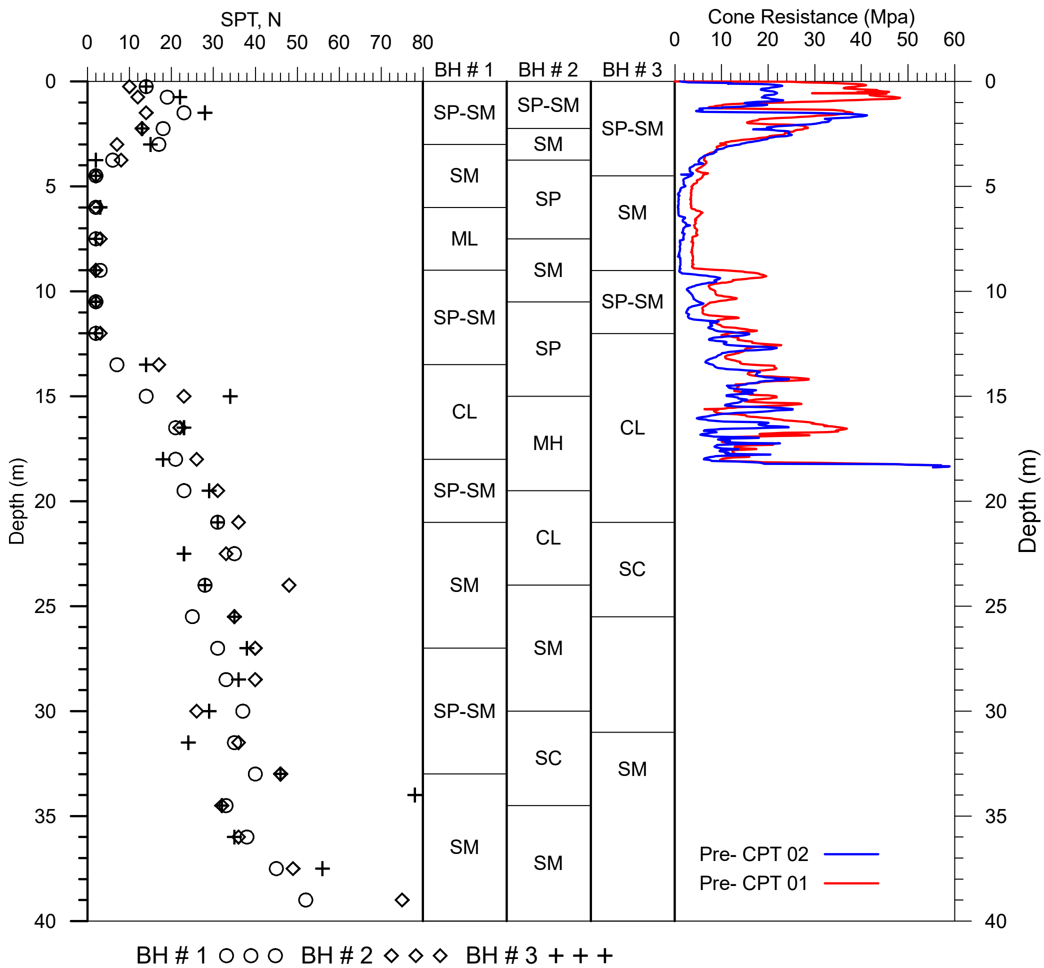

Figure 2: SPT, N values, PCPT test, and the subsurface strata encountered in boreholes.

4. Foundation System

The geotechnical expert has specified that a minimum bearing capacity of 200 kPa must be reached and taken into consideration during the foundation design process. According to the geotechnical investigation that was done on the site, the bearing capacity ranged from 85 to 145 kPa. After thoroughly researching several various foundation options, the final design of the foundation was narrowed down to two solutions that were both acceptable. Firstly, pile foundation to reach stable soil layers under sabkha soils. Secondly, soil improvement should be carried out in loose layers that are present down to a maximum depth of 13 m below the existing ground level. Soil improvement with the stone column approach is more efficient in this project. It was selected as the best appropriate technique due to its flexibility with soil type, depth of improvement, cost, and time. Piles could be used for foundations when there is only a limited defined area available or when the superstructure is transferring heavy loads.

The substructures consist of four piers fixed on a raft foundation, and the soil under the raft foundation was improved by stone columns. The adopted foundation system is presented in Figure 3. The stone columns are suggested to be installed on a square grid at a spacing of 1.3 m c/c. Based on the design calculation, the proposed stone column diameter is 0.85m and the treatment depth is up to 12 m below bottom of mat foundation.

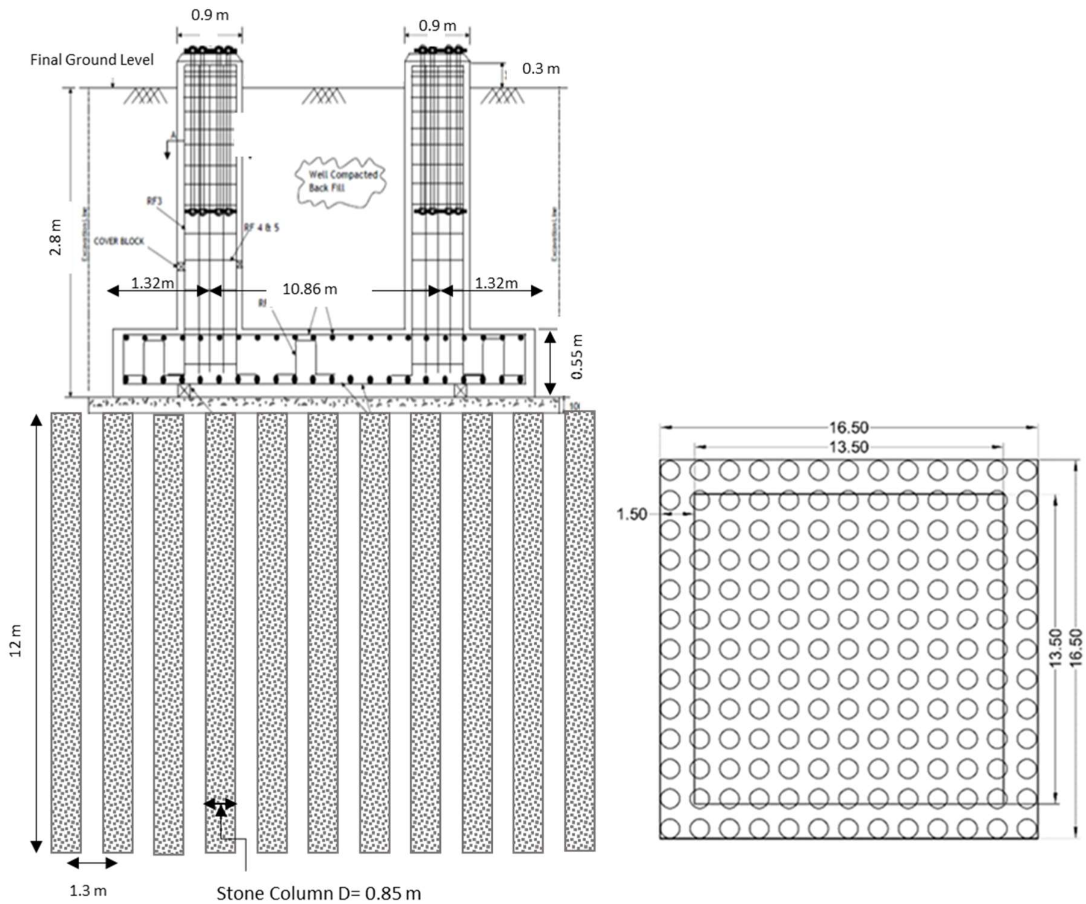

Figure 3: Dimensions of the Tower Foundation and a top view of the improvement area.

5. Soil Improvement

The purpose of the ground improvement works supported by stone columns is to achieve a design bearing capacity of 200 kPa for the tower foundation. The maximum uniform settlements to be achieved during operation is 25 mm. Based on the site characteristics, equipment availability, and previous experience, the Vibro-replacement top feed-wet method of installation was chosen for the project to prevent total and differential settlement and meet the required bearing capacity. Stone columns will have an effective length of 12m from -2.8m to -14.8m under mat foundation $(13.5\ m \times 13.5m)$. The stone columns were installed in a regular triangular grid of 1.3 m x 1.3 m with a diameter of 0.85 m. The total number of stone columns is 169, see Figure 3.

In Vibro-replacement, a powerful torpedo-shaped horizontally vibrating poker (Vibroflot) is used to make a hole in the ground in which a compacted stone column is generated. Figure 4 shows cross-sections of typical top-feed vibrators. The wet technique is often utilized if borehole stability is questionable. Consequently, it is appropriate for areas underlain by very weak and with a high ground water table. The wet technique makes use of stones or gravel with sizes ranging from 30 mm to 80 mm in size and the treatment depth can be increased to up to 30 meters [15].

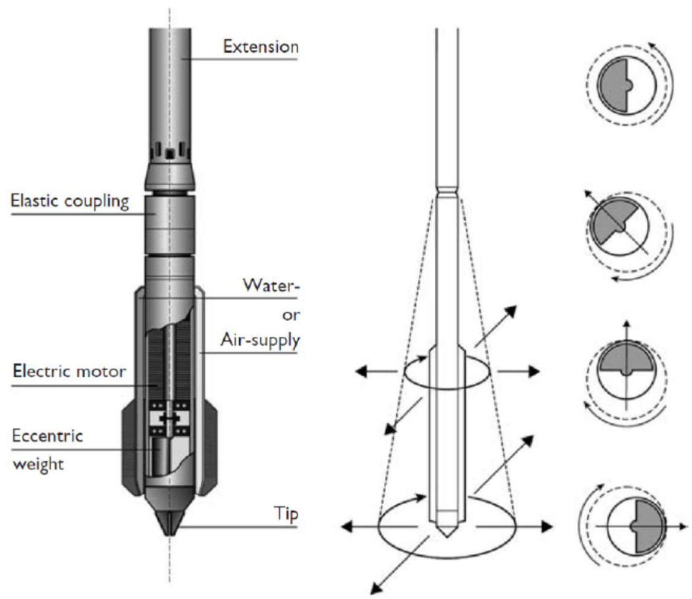

Figure 4: Vibrator and Principle of Vibro replacement (20).

Using a crane, an extension tube-mounted vibrator is put over the desired location to generate a stone column. Following the start-up of the motor and increased water jet, the soil in the immediate surroundings of the vibrator becomes saturated with water, resulting in local and temporary liquefaction under the effect of the vibrating motor and water jet. The oscillating vibrator, with its extension tubes, penetrates the soft soil under its own weight. The water flush, which will be cycled under pressure using Vibroflot, will be utilized to maintain the hole open and to wash off soft soil, which will be replaced with compacted stone columns. At this point, the coarse-grained fill material is dropped in small increments around the vibrator, which sinks to the bottom of the hole after it has achieved the desired treatment depth. The vibratory influence of the Vibroflot is used to compact stone columns, which is accomplished by moving the vibrator gradually up and down in a vertical direction. This procedure repeated in increments of approximately 0.5 to 1 m up to the ground surface, culminating in a densely compacted column of stones at the end of the process. Except for cohesive layers, which do not respond to vibration, Vibrofloat compaction increases the density of the surrounding soil. The installation process of the wet method is shown in Figure 5.

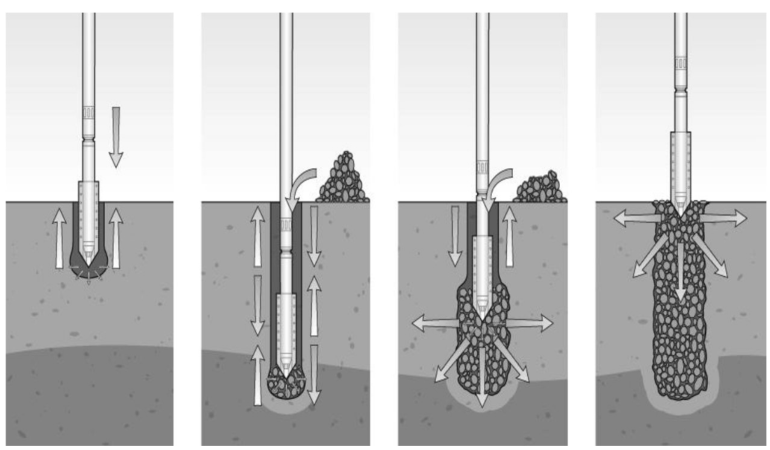

Figure 5: Installation Process by the top feet- wet Method.

For the equipment used by contractors, pressure is used to monitor the compaction of stone columns. The gauge pressure is related to the resistance offered by the stone column aggregate material being compacted. The pressure increases as the material gets compacted, and for a gauge pressure of 200 bars, the desired maximum compaction of the ground is achieved. Stone columns compacted up to a maximum of 220 bars of pressure. The images in the Figure 6 are from actual construction sites.

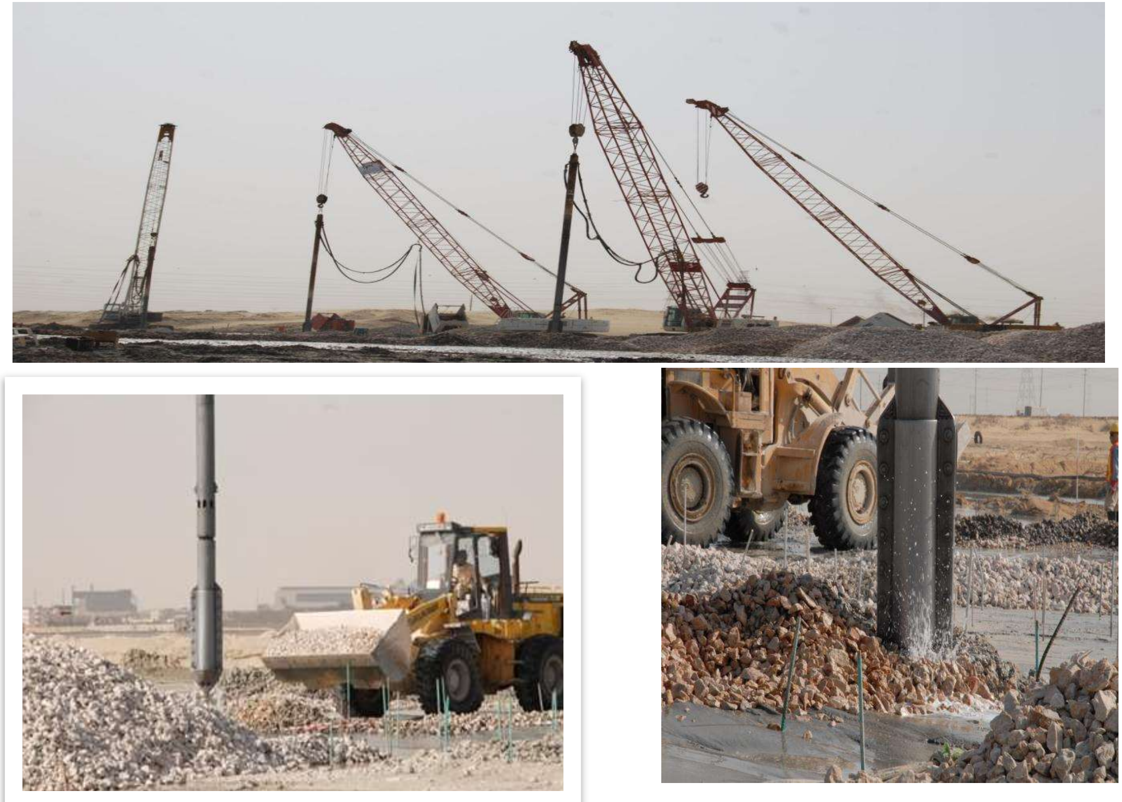

Figure 6: Installation of stone columns on-site.

6. Quality Control and Quality Assurance

Considering the changes in soil conditions before and after the installation of stone columns will lead to a better understanding of the performance of stone columns. It will be easier to understand the behavior of stone columns if the changes in soil condition surrounding the columns are considered. In this study, the PCPT tests were performed to assess the ground conditions before the installation of stone columns and to evaluate the degree of improvement achieved in the surrounding soils after installation. Plate load tests were also undertaken to verify the bearing capacity of the composite region, which included stone columns and surrounding soils. Details of these tests are presented in the following sections.

6.1. Pre & Post PCPT Test

It is more appropriate and desirable to use the PCPT than the usual Standard Penetration Test (SPT) for quality assurance and assessment of ground improvement activities that involve the installation of stone columns [16]. Different factors affecting the PCPT resistance value, including soil type, soil density, in-situ pressures, stress history, and soil compressibility [17], [18]. These tests provide full depth profiles against the design depth of stone columns, allowing a comparison of unimproved and improved soil conditions to the full depth. The record of Pre- and Post- PCPT tip resistance conducted around stone columns is shown in Figure 7 and Figure 8. Another method for assessing the effect of the installation stone column is to compare the tip resistance between post-PCPT and pre-PCPT readings. The following is how the ratios are expressed:

$$Tip\ resistance\ ratio, Q_R = \frac{q_{t(Post-CPT)}}{q_{t(Pre-CPT)}} \quad (1)$$

Where:

$q_{t(Post-PCPT)}$: Cone tip resistance of soil before installation of stone columns.

$q_{t(Pre-PCPT)}$: Cone tip resistance of soil after installation of stone columns.

The data shows slight improvement in the sandy layers above sabkha (0 to 3 meters) where sand or sand with silt is present. It was also observed that some of the pre-PCPT values are greater than the post-PCPT values, which validates A. Abas's (2015) hypothesis that this is due to the disruption of cemented soil bounding during the wet vibro-replacement activity and a lack of surface confinement [4]. Nevertheless, there was a noticeable improvement in the sabkha layer, particularly in the upper 1–3 meters of the stratum. The Sabkha's sandy, clayey composition, with shell fragments mixed in with sand from the top layers, could explain the improvement. This improvement could be explained by the sabkha soil in this location, which is classified as sandy soils with shell fragments and a fine content of less than 20%. The sabkha under 6 m below ground level contains fine soils more than 50 percent. Field observations have demonstrated that vibro compaction techniques are ineffective in improving the density of soils when the fine content exceeds 20% (24). This was confirmed by Hussin (1987) and Mackiewicz (2007), who found that vibro compaction techniques had no significant effect when the fine materials reached 12 percent [19], [20]. The soil under sabkha was classified generally as sand, and the value of pre-CPT increases with depth, reaching refusal at a depth of approximately 11 to 12 m. As shown in Figure 7 and Figure 8, the depth of refusal points in the post-CPT test decreased by more than 5 m. The reduction in refusal depth demonstrates that this layer has earned minor improvements because of the stone column installation process.

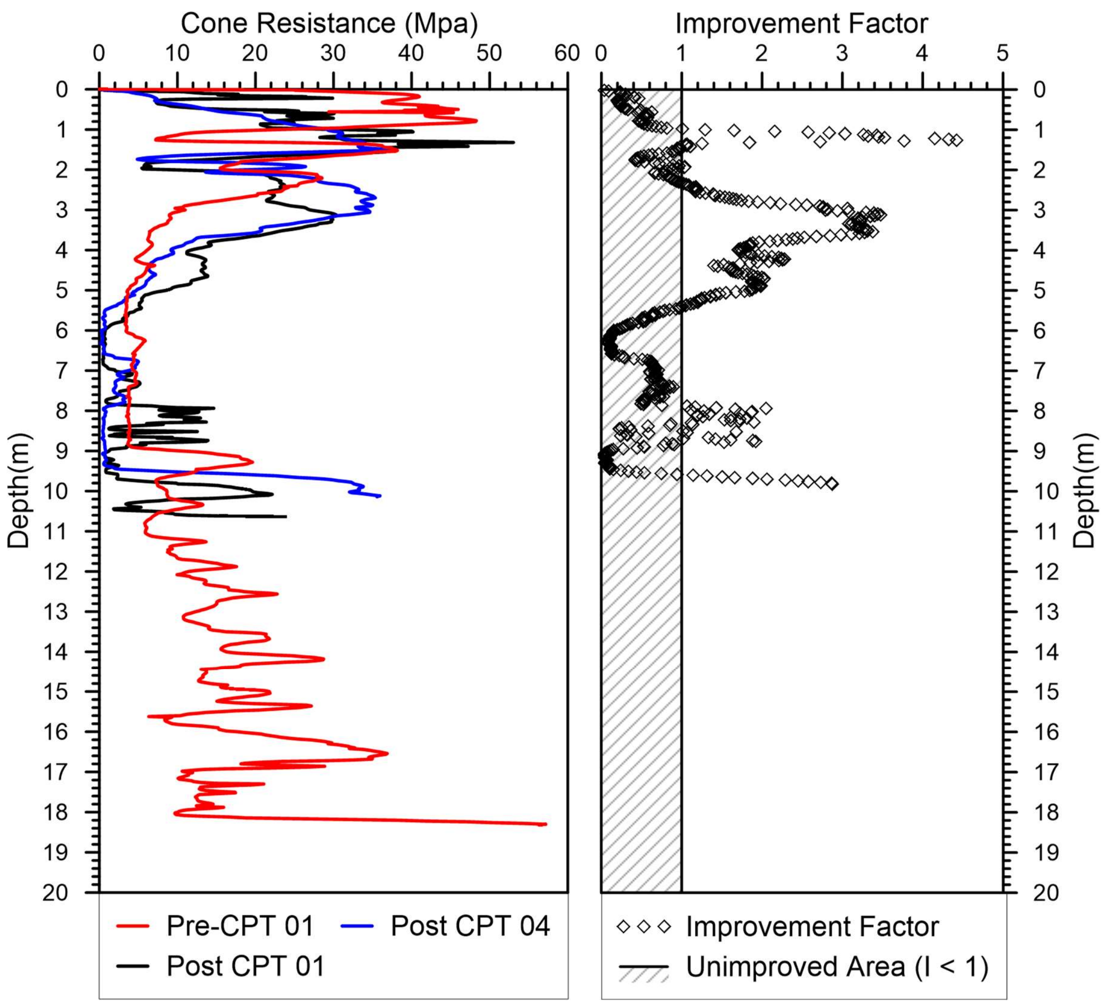

Figure 7: Pre-and post-PCPT in the soil improvement area.

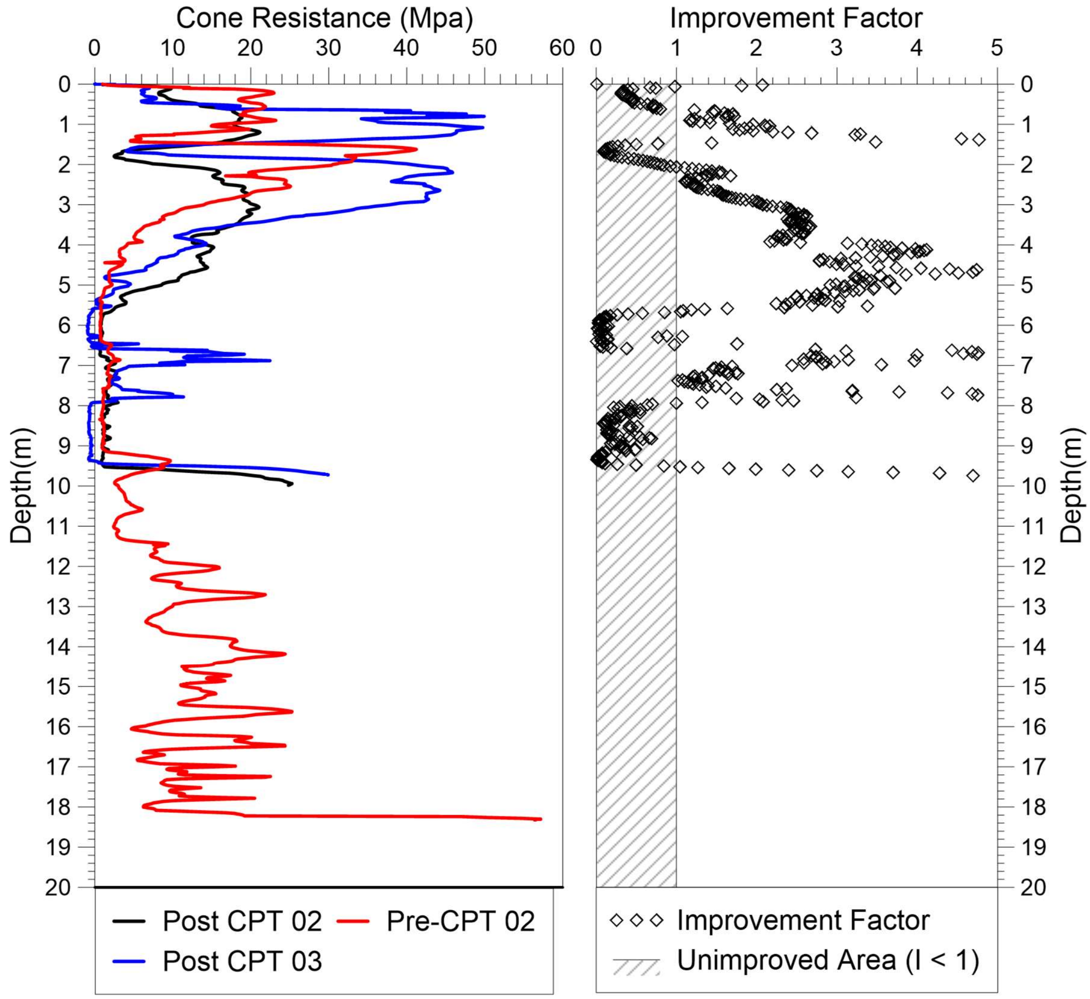

Figure 8: Pre-and post-CPT in the soil improvement area.

6.2. Footing Load Test

Footing load tests were performed to confirm the requisite design capacity of the composite area, which included natural soils and the stone column. The concrete footing utilized is 2 m × 2 m in dimension and 0.6 m thick. The footing was loaded according to the loading schedule shown in Table 1. The maximum applied stress is 300 kPa, which is 1.5 times the required bearing capacity. The pressure was applied to the concrete footing by a hydraulic jack reacting against a 120-ton kentledge platform of concrete blocks (see Figure 9). The relationship between applied load and settlement is depicted in Figure 10. The test was carried out in accordance with ASTM D1194. According to the test results, the maximum value of settlement is 2.44 mm, which is only 9.8 % of the maximum allowable settlement of 25 mm.

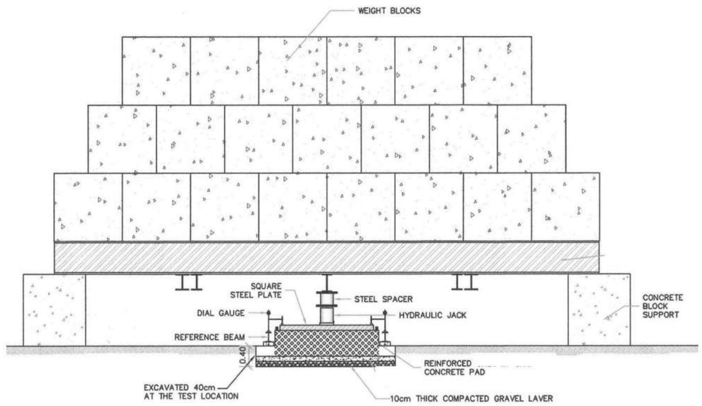

Figure 9: A plate load test setup.

Table 1: Summary of concrete footing.

An example of a column heading	200	300	Zero
Total Settlement (mm)	1.35	2.44	0.27
Acceptance Criteria (mm)	25	25	25

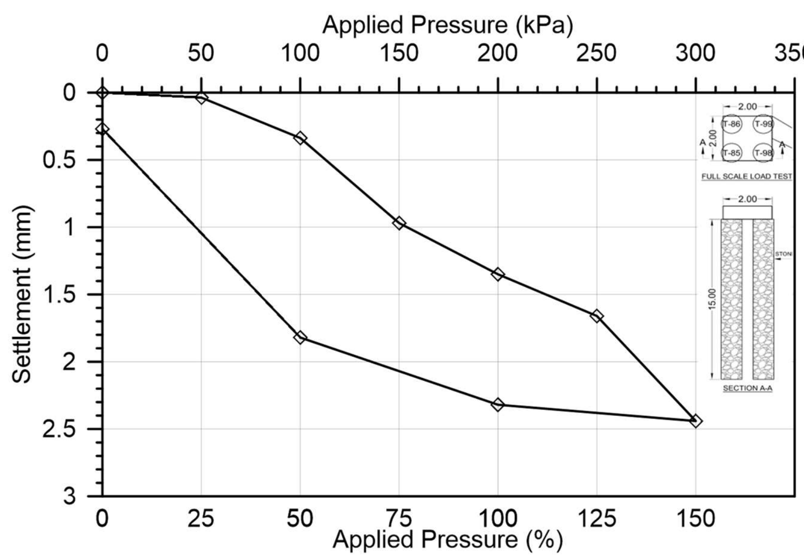

Figure 10: The results of the plate load test.

7. Conclusion

The paper presents a case study of the installation of stone columns to improve sabkha soils. The relevant data of soil conditions, foundation systems, construction procedures, and field control criteria were presented and discussed. A review of the data discussed in this paper demonstrates that vibro replacement is efficiently used under tower foundations that meet increased bearing capacity requirements and stringent settlement criteria. The following conclusions were drawn from the outcomes of this study:

1. Due to the nature of lattice structures, which are frequently erected in series and repetitively, companies tend to underestimate the importance of soil investigation by not taking a significant quantity of samples and evaluating them for cost-saving. Soil investigation costs are approximately less than 1 percent of a project's cost, therefore it is a negligible cost compared to the reliability and uncertainty clearance that are offered for foundation design.

2. Stone columns are a well-established ground improvement technique that has proven to be efficient in improving the bearing capacity and decreasing post construction settlement in sabkha soil layers. It's critical that the stone column spacing, and depth be optimized in order to maximize the benefits of this method.
3. In this project, soil improvement utilizing stone columns was found to be more efficient than pile foundation. In terms of both cost and time.
4. The installation effect of Vibro-stone columns resulted in significant improvement in the sand layer above sabkha and minor improvement in the sabkha layer.
5. The reduction in refusal depth of pre-PCPT and post-PCPT reveals that the sand layer under sabkha soils has earned minor improvements because of the stone columns installation process.
6. The Full-Scale load test results have shown excellent improvement in the ground conditions. The maximum settlement of load test footing at 100% of the Design Pressure was recorded as 1.35 mm while settlement at 150% of Design Pressure was 2.44 mm only.

8. Acknowledgements

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9. References

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