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A model study of axially loaded micropiles in layered soils

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Abstract. The current research uses a physical model to investigate the role of micropiles as vertical reinforcement of footing when embedded in sandy silty soil from Mosul city – Iraq. The experimental program focused on carrying out several load-settlement tests for the footing with two different reinforcement conditions: by a single micropile and group micropiles. The study is extended to investigate the role of soil homogeneity, weak soil underneath by strong soil layer, in the behavior of load-settlement curves for the reinforced footing. Next, the load settlement tests were, again, conducted using the same model but for the non-reinforced footing (flat footing). The first results indicated that the physical model has succeeded in representing all the studied cases. Also, the results showed a significant improvement in the behavior of the load-settlement curves when the footing was reinforced with micropile, especially using the micropile group, compared with the non-reinforced footing. Also, the degree of improvements in the load-bearing capacity and load-settlement behavior, for the footing reinforced with micropiles embedded in different conditions of soil homogeneity, was examined through two different non-dimensional factors: bearing capacity ratio (BCR) and percent of settlement reduction (PSR). The results indicated that the BCR was increased and the PSR was decreased for the reinforced footing compared to the non-reinforced footing. Moreover, from the test results, we noticed that the homogeneity of the soil has a significant effect on the load-settlement curves behavior of the footing.

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1. *Introduction*

Since ancient times, humans have tried establishing strong buildings that could last for hundreds of years. Many buildings, consisting of stone and light materials, were erected. In nature, soil exists with a wide range of variety in its bearing capacity. Therefore, it was necessary to use different foundation types commensurate with the nature of the soil in the field and with the number of loads transferred to it. Micropiles are considered a modern foundation type that proves successful in the practical field. They were called "Micropiles" due to their small diameter, which ranges from ten to thirty centimeters, and their light weight. Micropiles are usually executed by injection of the cement mixture with or without using steel reinforcement. Recently, technological advances in machinery made it possible to implement micropiles with different small diameters. Whether in the static or dynamic state, the micropiles are a type of foundation that can work, mainly using friction, as an integrated system to transfer the loads from the structures to the layers of the soil. The purpose of micropiles work is to improve the bearing capacity of the soil by increasing the density, increasing the confinement of the soil surrounding the micropile, and consequently creating friction [1].

Micropiles are characterized by the possibility of improving the weak soil layers (i.e. by reinforcing the foundations of existing buildings, especially ancient archaeological buildings). The micropiles also contribute to the consolidation of the foundations of buildings in cramped places that are difficult to reach by massive machines [2]. Likewise, Micropiles play an decisive role in stabilizing deep excavations for new strategic projects to be implemented in places with limited spaces in crowded cities, and in the case of projects that are difficult to reach using machines for traditional piles, here micropiles must be used [3]. The micropiles are also characterized by their rapid implementation compared to the implementation of traditional piles with large diameters [4]. In addition, because the execution of micropiles does not require the use of large equipment, as is the case in the execution of other traditional foundations, thus the selection of micropiles does not result in destructive and harmful vibrations to neighboring buildings [5]. Due to the distinctive features of micropiles, many projects have adopted using micropiles in unlimited scope and have proven to be functionally successful.

The first use of micropiles was in the mid of the twentieth century when they were invented for the first time in Italy to support the foundations of the Anguilli School in Naples by engineer Fernando Lizzi [6]. In North America, specifically on the East Coast of the United States, micropiles witnessed wide interest in the seventies [7]. In Japan, again, micropiles were used in eighties to support the foundations of a lookout tower [8]. Moreover, the researchers [9] indicated that China used micropiles in the eighties as a new experiment through the study of representing a laboratory model to simulate the reality of the Uu-Qui tower. Furthermore, Hong Kong also paid attention to the first studies on micropiles through the published research of [5], where it was recommended to use micropiles in construction conditions that need as little disturbance as possible for neighboring buildings. Locally, micropiles were used in consolidating the Al-Hadbaa minaret foundation in Mosul city - Iraq, as part of the maintenance work carried out by the Italian company in the early eighties [10, 11], Fig. 1.

Through the efforts made by many researchers, scientific research institutions, and universities, including the Federal Highway Administration of the US Department of Transportation [12] in the field of carrying out, and studying the behavior and design methodologies of the micropiles, therefore the micropiles have been used all over the world with their proven track record of success [13]. Finally, it must be noted that the use of micropiles has taken place in development projects and urban and industrial redevelopment, and here the selection of the characteristics of micropiles (length and diameter of micropile, and the angle of inclination while fixing micropile to the soil) depends on the type of soil, the depth of the foundation, groundwater, and the type of loads (tension or compression).

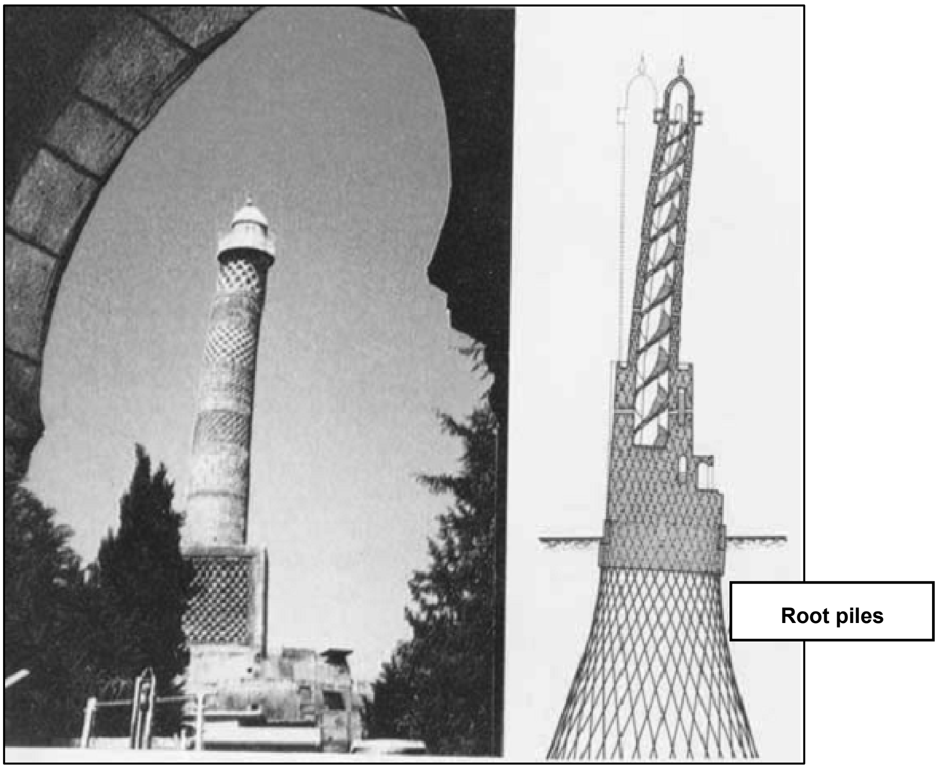

Figure 1. The use of micropiles in consolidating the Al-Hadbaa minaret foundation, (Lizzi, 1982; 1997).

Many previous studies focused on studying the behavior of micropiles (bearing capacity and settlement of foundation) and the extent to which they are used, whether in reinforcement and treatments of pre-existing foundations or in the field of using them as a foundation when constructing vital engineering projects.

In [14] the researchers were interested in using a laboratory-physical model to study the possibility of reinforcing fly-ash soil using micropiles. The laboratory model was represented numerically using SIGMA/W of GeoStudio 2016 software. The numerical study was adopted to investigate the bearing capacity and settlement of the foundation with different conditions of micropile length, the distance between micropiles, and the distance of the micropiles extending beyond the foundation edge. The researchers concluded from this study that the bearing capacity increases with the increase of the micropile length. Another conclusion is that, when the distance between the micropiles reduced and the piles extends beyond the edge of the foundation increased, there are increases in the bearing capacity and decreases in the settlement of the foundation.

Away from fly-ash soils, the research work of [1] focused on studying the behavior of the micropiles in the case of sandy soils. Once again, the studied variables are the micropile diameter, length, the distance between the micropiles, and the distance of the micropiles from the edge of the foundation. The laboratory results showed that the foundation increased in its bearing capacity and decreased in its settlement in case of increasing the diameter and the length of the micropile and decreasing both the distance between the micropiles and the micropiles distance to the foundation edge.

The behavior of micropiles in sandy soils was studied extensively by previous research works [15–19]. The laboratory model proposed by [15] revealed the effect of five different parameters (degree of inclination, diameter, length-to-width ratio, spacing between micropile, and the closeness of the micropiles to the footing) on the behavior of micropiles footing. The inclination of micropile was more effective in the case of horizontal loading than vertical loading. The micropile diameter and the length-to-width ratio enhance the bearing capacity of micropile footing. The degree of micropile closeness to the footing and the decrease in the spacing between the micropile increase the bearing capacity of the micropile footing.

In [16] the researchers carried out a series of model tests on group micropiles to reinforce the footing resting on sandy soils with different densities. The study showed that the sandy soil with different degrees of confinement (dense, medium, and loose) led to induce different mechanisms in the behavior of group micropile: the positive dilatant behavior of dense sand led to a significant improvement of the micropile footing.

On the other hand, the mode of failure of the group micropiles implemented in the sand and subjected to vertical or oblique pull-out loads was examined [18]. The most important finding of this study is that micropiles with a high length-to-diameter ratio can fail in two different modes: soil failure and structural failure. The former failure mode belongs to the group of vertically pulled micropile, while the latter mode of failure belongs to the group of micropiles subjected to a load pulling with a high degree of obliquity.

In another aspect, in a study conducted by [19], a laboratory model was used to apply inclined compressive loads on a group of micropiles implemented in sandy soil with different spacing between the micropiles and different length-to-diameter ratios of the micropiles. The study concluded that the lateral capacity of the group micropiles increases with increasing the length of micropiles and the spacing between the micropiles.

After demonstrating the literature review above, it can be said that most of the previous studies attempt to investigate the behavior of micropiles in homogeneous sandy soil. In contrast, the studies of the micropiles in layered soils are rather limited, especially for the silty soil type. Therefore, the current research work adopts the use of a physical model to study the behavior of micropiles in heterogeneous silty soils in two different cases: when the silty soil surrounding the micropiles has a homogeneous layer (the soil density is constant for the entire single soil layer), and the silty soil is two-layered (the soil in the lower layers has a density greater than the soil in the upper layer). Again, the previous studies have not fully addressed the behavior of micropiles that are implemented in layered soils. Moreover, such type of study has not previously covered in the case of micropiles implemented in local soils from Mosul city - Iraq. Therefore, it can be said that the distinctive objectives of this study are:

- Characterization of the local soils from Mosul city near the Tigris River basin, with a particular focus in recent years in the exploitation and investment of lands near the site of the current study area.
- Investigating the possibility of using a physical model to simulate the behavior of micropiles in the field.
- Representation of the soil in the physical model with different states of soil stratification.
- Characterization, in details, the bearing capacity and settlement of the micropiles when implemented in the local soil in two different states: layered and non-layered.
- Determining the ultimate bearing capacity of the foundations by four different graphical methods with comparing the obtained ultimate values.

2. Methods

2.1. Selection and Properties of Soil

The natural soil samples of this study are brought from Khawaja Khalil village. Khawaja Khalil is located in the alignment of the Tigris River on the left coast of Mosul city – Nineveh Governorate, Iraq, Fig. 2. The excavations were carried out to a depth of approximately 2.5 m. During the field campaign, two types of soil samples were excavated: disturbed and non-disturbed soil samples. These soil samples were wrapped to avoid changes in the moisture content. Later, the soil samples were transferred to the Geotechnical Laboratory at the University of Mosul to conduct some of the physical and mechanical laboratory tests that help us in soil characterization.

Physical tests were conducted on soil samples based on the method adopted by the American Society for Testing and Materials (ASTM). These tests included: natural moisture content, natural dry density, specific gravity, Atterberg limits, and soil grain gradation by both dry and wet analysis.

In light of the Atterberg limits test and the sieve analysis test, one can identify the liquid limits, the plasticity index, and the percent of gravel, sand, silt, and clay materials of the tested soil. Thus, a soil sample can be classified according to the Unified Classification System (USCS). The details of these tests are listed in Table 1. Again, a set of mechanical tests: the standard Proctor compaction test, modified Proctor compaction test, and direct shear test, were performed on soil samples, and the results of these tests are listed in Table 1.

According to the USCS, the data analysis of the physical and mechanical tests proved that the soil in the current study is silty soil with low plasticity (ML) of group name (sandy silt). Also, the soil samples can show good shear strength resistance: the shear strength parameters ranged between 27–34 degrees and 8–13 kPa as the angle of internal friction and the cohesive force, respectively.

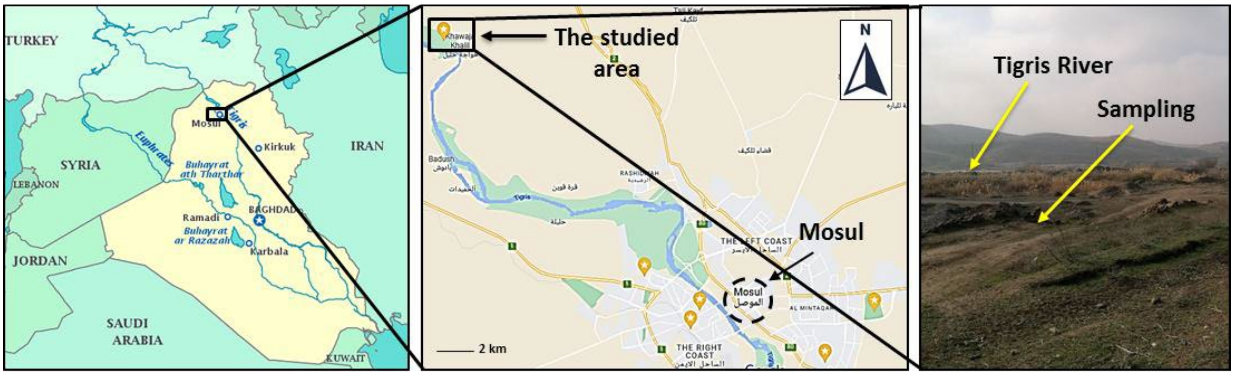

Figure 2. Location of the studied area.

Table 1. Physical and mechanical properties of the studied soil.

Parameter		Values	Test procedure
Natural water content, (%)		9.80	ASTM D 2216, 2010**
Natural moist unit weight, (kN/m^3)		16.30	ASTM D7263, 2018**
Natural dry unit weight, (kN/m^3)		14.84	
Specific gravity		2.67	ASTM D854 – 14**
Atterberg limits	Liquid limit, (%)	NP	ASTM D 4318, 2017**
	Plastic limit, (%)	NP	
	Plasticity index, (%)	NP	
Percentage of soil grains	Gravel, (%)	10	ASTM D 6913M – 17** ASTM D7928 – 17**
	Sand, (%)	30	
	Silt, (%)	48	
	Clay, (%)	12	
Soil classification, (USCS)		ML: silt with low plasticity (sandy silt)	ASTM D2487 – 17**

Parameter			Values	Test procedure
Compaction test	SPE*	Max. dry density, (kN/m^3)	17.0	ASTM D1557 – 12**
		Optimum water content, (%)	16.0	
	MPE*	Max. dry density, (kN/m^3)	18.75	
		Optimum water content, (%)	12.0	
Direct shear test	SPE*		c = 8 kN/m^2	ASTM D3080M – 11**
			φ = 27^o	
	MPE*		c = 13 kN/m^2	
			φ = 34^o	

*SPE: Standard Proctor energy, and MPE: Modified Proctor energy
** [20]

2.2. Physical Model

Mainly, physical modeling is used to reduce the dimensions of the represented prototype. This reduction saves time, resources, and effort consumption. Also, the physical modeling facilitates the conduct of various tests in the laboratory and the interpretation of their results. Testing the performance of micropile by physical models requires using several tools and devices (soil containment tank, loading plate, micropile foundation, compaction machine, load cell for measuring the applied load, sensors for measuring the induced settlement, and a data logger). In this study, the physical model of the formative parts is described briefly in the following paragraphs.

2.2.1. The model tank and loading plate

In this experimental work, a tank made of rigid steel was used. The volume of the tank is suitable to contain a sufficient amount of soil pressed with axial static pressure loads, stress control, or strain control using a hydraulic piston. The used tank is a square cube with internal dimensions of fifty centimeters a side and a height of 60 cm, Fig. 3. The choice of the dimensions of the tank should be taken into account so that the depth of the tank model is more than ten times the diameter of the used micropile. This measure is to avoid the effect of the extension of the micropile stresses and the interaction with the bottom of the tank body while applying the axial loading [21].

The loading plate (square plate) is made of rigid steel with dimensions of ten centimeters a side and a depth of 0.6 cm, Fig. 3. Previous research indicates that choosing the dimensions of the loading plate and the dimensions of the model tank must be compatible so that the experiment is conducted without the tank walls affecting the distributed loads coming from the loading plate, i.e. the boundary effects [14]. This compatibility between the dimensions of the loading plate and the dimensions of the tank requires that the width of the tank be at least five times greater than the width of the loading plate [1, 22]. Moreover, the loading plate was designed with a rough surface enough to represent the actual roughness of the footing [23].

It is worth mentioning that the used tank should be well attached to an iron frame. The purpose of using this framework is to facilitate the implementation of the test at a constant loading rate on the one hand and to collect data correctly without disarrangement on the other hand. Thus, the obtained data can be analyzed accurately and with complete control over the test conditions.

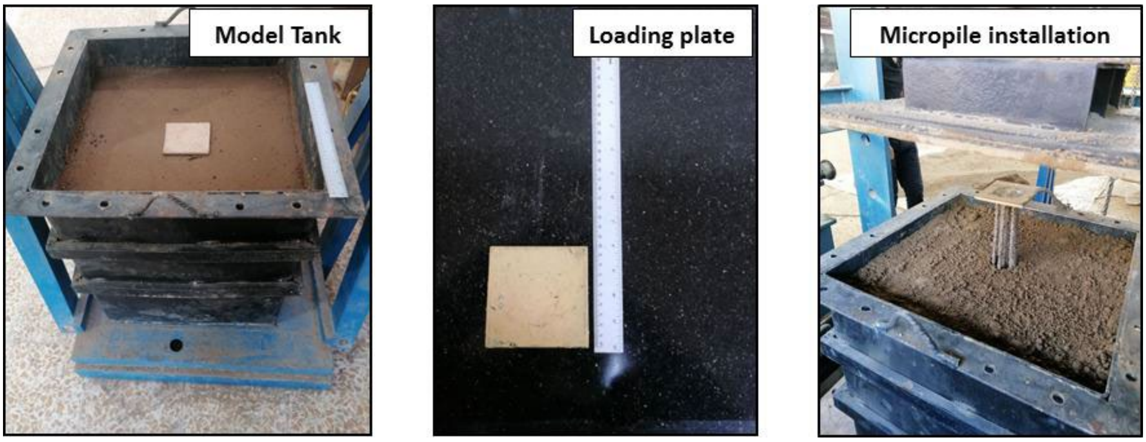

Figure 3. The model tank (left), loading plate used in the physical model (middle), and the process of micropile model installation (right).

2.2.2. The micropile foundation

Previous studies indicate that the micropile model was represented experimentally by using micropiles made of different materials; a rod of steel [1, 14, 16, 24–26], a rod of Aluminum [15, 27], a rod of Polyvinyl Chloride (PVC) [16, 28–31], and even rod of Bamboo sticks [32–34]. The foundations used in this study are composed of a loading plate and reinforced with piles (single or group micropiles). The micropile model used in this study with a diameter of 6 mm and a length of 300 mm and is made of stainless steel.

Following the procedure outlined in the work of [24], the micropiles were fastened to the loading plate: the loading plate has been reinforced with micropiles, where the micropiles were welded in the center and perpendicular to the surface of the loading plate to avoid the eccentricity of the loading. Concerning the micropiles group, the mode of reinforcing the loading plate with micropile was done using the honeycomb shape with seven micropiles, Fig. 4. In this case, the distance between the micropiles is even and equal to four times the diameter of the micropile [32]. Choosing the distance between the micropiles of the group four times the diameter of the micropile (greater than three times the diameter) is to ensure avoiding interaction between the micropiles [13]. The smooth surface of the steel rods (micropile model) was coated with a thin layer of sand to make the surface rough (to impose the skin friction) and to represent the condition of the micropiles in the field [15, 16, 28, 31]. Fig. 4 shows the conditions of the micropile model used in the study. Here it is worth noting that the reason for using a honeycomb shape (hexagonal) pattern of micropiles distribution is to make the distance between all micropiles equal (even the diagonal distance between the central micropile and the micropiles located at the ends), and this cannot be achieved in the case of using a pattern of regular micropile distribution such as the square shape or the rectangular shape.

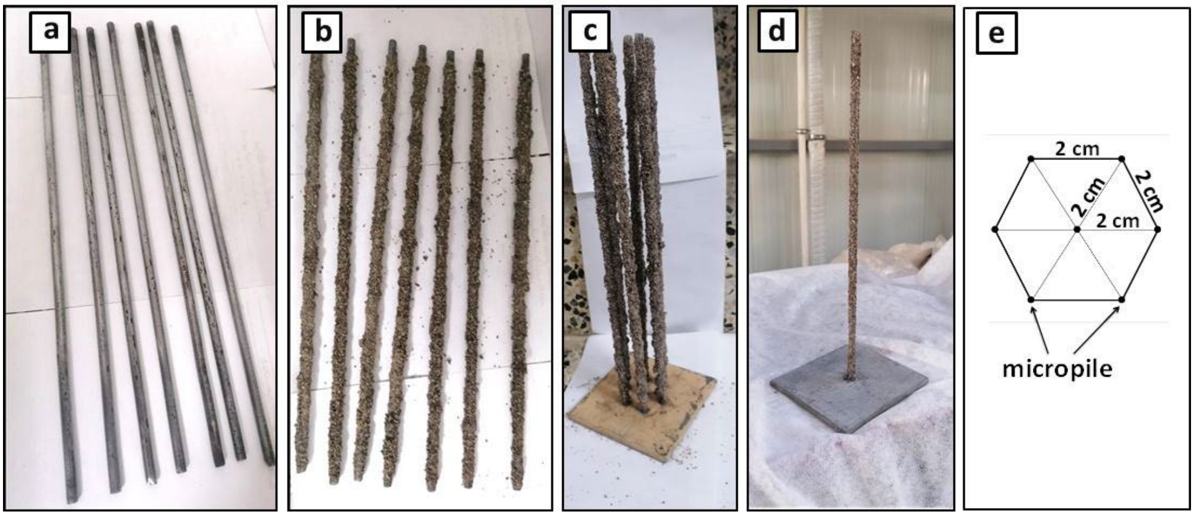

Figure (4) The stainless steel micropiles model, a) before gluing with sand, b) after gluing with sand, c) group micropiles, d) single micropile, and e) top view of the micropiles model with honeycomb shape.

2.2.3. Soil beds and micropile installation

Before conducting the soil deformation test, the soil layers inside the physical model were prepared with a maximum dry density of standard or modified Proctor compaction test. To this end, a certain amount of water, at optimum water content, was added to the dry soil. Later, a certain weight of pre-mixed moist soil was compacted statically into the tank at a constant rate using an electro-hydraulic press machine. To achieve the requisite soil dry density of 17.0 and 18.75 kN/m^3, which correspond to the maximum dry densities for the standard and modified Proctor compaction tests, respectively, the soil mixture was compacted in five stages, each lasting 100 mm. After completing the compaction process for each stage, the density of the compacted soil was checked by inserting a small mold inside the compacted soil layers to measure the soil density. At the end of the fourth stage of soil compaction (at a height of 400 mm of soil inside the tank), the micropiles were pushed inside the soil layers during the soil compaction process in the fifth stage [1], as shown in Fig. 3. By following this method, we ensure that the micropiles are well installed inside the soil beds while reducing the disturbance of the soils surrounding the micropile to as little as possible. It is pertinent to note that the electro-hydraulic press machine was utilized to set the micropiles into the soil inside the model tank. The penetration of the micropiles is controlled with a constant penetration rate of 1.0 mm /min.

2.3. Loading the Micropile

In this experimental work, the process of applying the loads was done with the help of a rigid loading frame by using a hydraulic jack. Multiplicative increments of loads (0.25, 0.5, 1.0, 2.0, 4.0, … kN), were applied during the test. The previous studies indicated that the laboratory tests for the physical model are usually done by loading the micropiles and recording the settlement until reaching different values of the settlement ratio (Sr = s / b), where (s) is the settlement, and (b) is the width of the footing. For instance, the recorded settlement ratio is: Sr = 13 % [15], Sr = 16 % [24], Sr = 25 % [25], and even Sr reaches a high value of about 70 % [28]. In this study, the load increments were applied during the test until the reaching the failure: excessive settlement at a certain load or the maximum settlement of 50 mm (i.e. Sr = 50 %). The loads were applied at a constant rate of 1.0 mm/min.

2.4. Load and Settlement Recording

Concerning the load and settlement data recording, a set of tools was used for this purpose: the load cell, the displacement gauges, and the data logger. The Z beam load cell with 50 kN capacity was used to measure the applied loads. The range of temperature was from negative thirty to positive seventy centigrade is accepted by using such a type of load cell. The vertical displacement was measured by the linear variable differential transformer-LVDT, with a displacement range of 50 mm. Again, this displacement transducer LVDT is workable at a temperature range from negative ten to positive sixty centigrade. Three LVDTs were utilized to measure the settlement of the loading plate during the test. These three displacement transducer LVDTs are set at an angle of 120° to cover the entire loading plate. The average value is taken from the three LVTDs. Also, the data logger of type TDS-530 was selected to read the data: load and settlement, Fig. 5. This device is capable of reading data from 20 channels simultaneously. By using these tools, the accuracy of measuring the settlement and the applied loads during the experiment was 0.001 mm and 1 kN, respectively. These data were recorded every second to monitor any change that could occur during the progress of the test. The collected data in Excel file format was uploaded to the computer once each test was finished. The recorded data resulted in the analysis of an average of 8,000 rows in the Excel file for each test. Again, Fig. 5 shows a set of tools used in this study and the test setup.

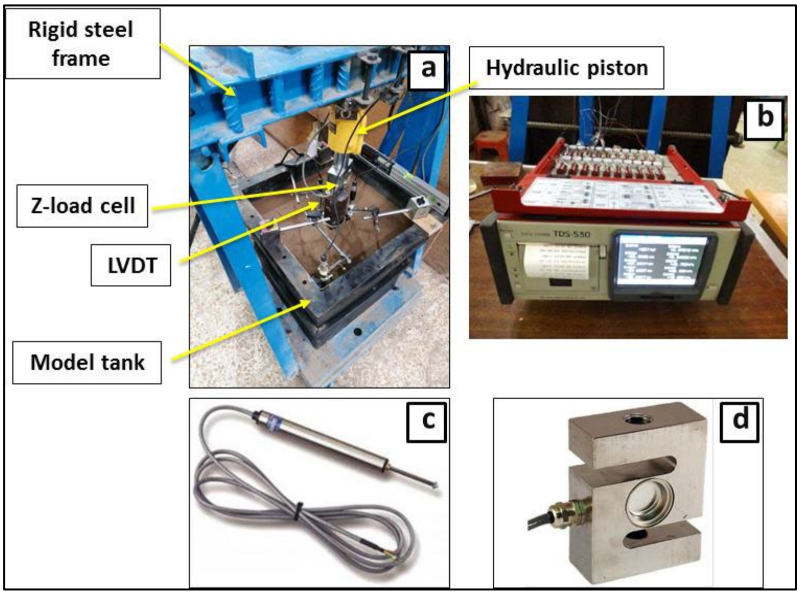

Figure 5. Set of tools used in the physical model and test setup during the test.

2.5. Test Series

The current experimental work included carrying out the loading tests with two different soil stratification cases: the first case is for the non-stratified soil condition (the whole soil inside the tank prepared with the density of standard Proctor compaction energy). The second one represents the stratified soil condition (the upper soil layers with a thickness of 20 cm inside the tank were prepared with the density of standard Proctor compaction energy, while the lower layers with a thickness of 30 cm were prepared with the density of modified Proctor compaction energy).

Three footing reinforcement scenarios were tested for both types of soil conditions: the first scenario involved reinforcing the footing with a single micropile, while the second scenario involved reinforcing the footing with a group of micropiles. To compare the findings and acquire reference data for the loading-settlement tests, the third scenario was interested in the footing but without reinforcement (flat loading plate). Six experimental tests were completed as part of this study project using these various soil layer conditions and footing reinforcement scenarios.

3. Results and Discussion

The load-settlement test results for the footing with three different reinforcing cases (flat footing, footing reinforced with single micropile, and footing reinforced with group micropiles) are presented and discussed in this section. These tests involved embedding the micropiles in soils that were either homogeneous non-layered or heterogeneous layered.

3.1. Load-settlement Curves for Different Cases of Footing Reinforcement

Fig. 6 shows the load-settlement curves for three cases of footing reinforcement; the non-reinforced footing or flat footing (F), the reinforced footing with a single micropile (S), and the reinforced footing with a group of micropiles (G). For all the cases studied, the footing's load-settlement curves under an axial compressive load are non-linear. Fig. 6-a is interesting for the case of the soil layers inside the tank having a density of standard compaction Proctor energy (non-layered soil, "N L"). Also, Fig. 6-b shows the load-settlement curves for the same different cases of footing reinforcement shown in Fig. 6-a, but when the soil is layered "L", the tank contains soil in the upper layers having a density of standard compaction Proctor energy and the lower soil layers having a density of modified compaction Proctor energy). The difference in the type of footing reinforcement has a significant effect on the behavior of the load-settlement curves. In general, at a certain settlement, it is noted that there is a clear increase in bearing capacity when the footing is reinforced compared to the non-reinforced footing. The same observation can be seen when the footing is reinforced with a single micropile compared to a footing reinforced with a group of micropiles.

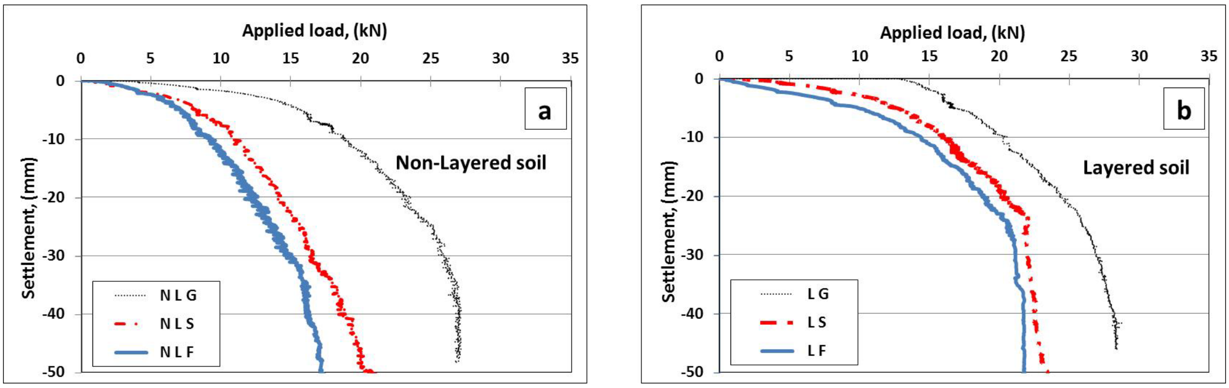

Figure 6. Load-settlement curves for different cases of footing reinforcement.

3.2. Load-settlement Curves for Different Cases of Soil Homogeneity

The curves in Fig. 6 show the load-settlement curves in the case of non-reinforced footing (flat footing) in two different cases of soil homogeneity inside the tank: heterogeneous layered soil (LF) and homogeneous layered soil (NLF). Furthermore, Fig. 6 show the effect of soil homogeneity on the behavior of the load-settlement curves in the case of a footing reinforced with a single micropile (LS and NLS) and a group of micropiles (LG and NLG), respectively. Once again, it is noted that there is a clear difference in the behavior of load-settlement curves depending on the case of soil homogeneity.

Regardless of the type of footing (flat footing, footing reinforced with a single micropile, or a group of micropiles), the curves presented in Fig. 6 denote that there is a clear increase in the bearing capacity of the footing or a clear decrease in the settlement at a certainly applied loading in the case of layered soil compared to non-layered soil. This occurs due to the improvement of the soil properties in the lower layers inside the tank since these soil layers have been compacted with the modified compaction energy. This, in turn, leads to an increase in the soil shear strength parameters (C and Phi).

On the other hand, in the current research work, the layered soil was made denser than the non-layered soil. This results in a commitment to change the failure mode from the local share failure state of the non-layered soil to the general shear failure mode of the layered soil. In this case, increasing the density in the lower layers of the soil inside the tank leads to an increase in the frictional resistance between the micropile and the surrounding soil, and this is another reason to justify the increase in bearing capacity of the footing embedded in the layered soil rather than the non-layered soil.

3.3. Determination of the Footing Bearing Capacity by Graphical Methods

In the case of shallow footing, the bearing capacity from the load-settlement curve can be easily distinguished, through which three natural bearing capacity failures in the soil can be named: general shear failure, local shear failure, and punching shear failure [35]. This is not the case in micropile footing, where it is difficult to identify the point of failure in the load-settlement curves. The graphical methods are usually used to find the bearing capacity of the micropiles. Below is a brief explanation of the most important of these graphical methods used in previous studies:

3.3.1. Tangent method

This approach involves creating two tangent lines for the load-settlement curve: the first line at the beginning of the curve and the second one at the end of the curve. The intersection of these two tangents can represent the bearing capacity of the micropile, Fig. 7-a.

3.3.2. Butler and Hoy method

In this method, a tangent line with a slope of 0.127 mm/kN is drawn to intersect with the initial tangent line of the load-settlement curve. The point of intersection represents the bearing capacity of the micropile [36], Fig. 7-b.

3.3.3. De Beer and Wallays method

This method is the same as the tangent method, but when the load-settlement curve is drawn on a logarithmic scale for both load and settlement axes [37], Fig. 7-c.

3.3.4. Corps of engineering method

This method is concerned with finding three load values from the load-settlement curve. The first load value (Q1) can be found when the settlement is 6.4 mm. The second load value (Q2) represents the load value obtained by the tangent method (as mentioned above). The third load value (Q3) represents the value of the load when the line with a slope of 0.025 mm/kN touches the load-settlement curve. Finally, the bearing capacity of the micropile could be calculated as the average of these three load values [38], Fig. 7-d.

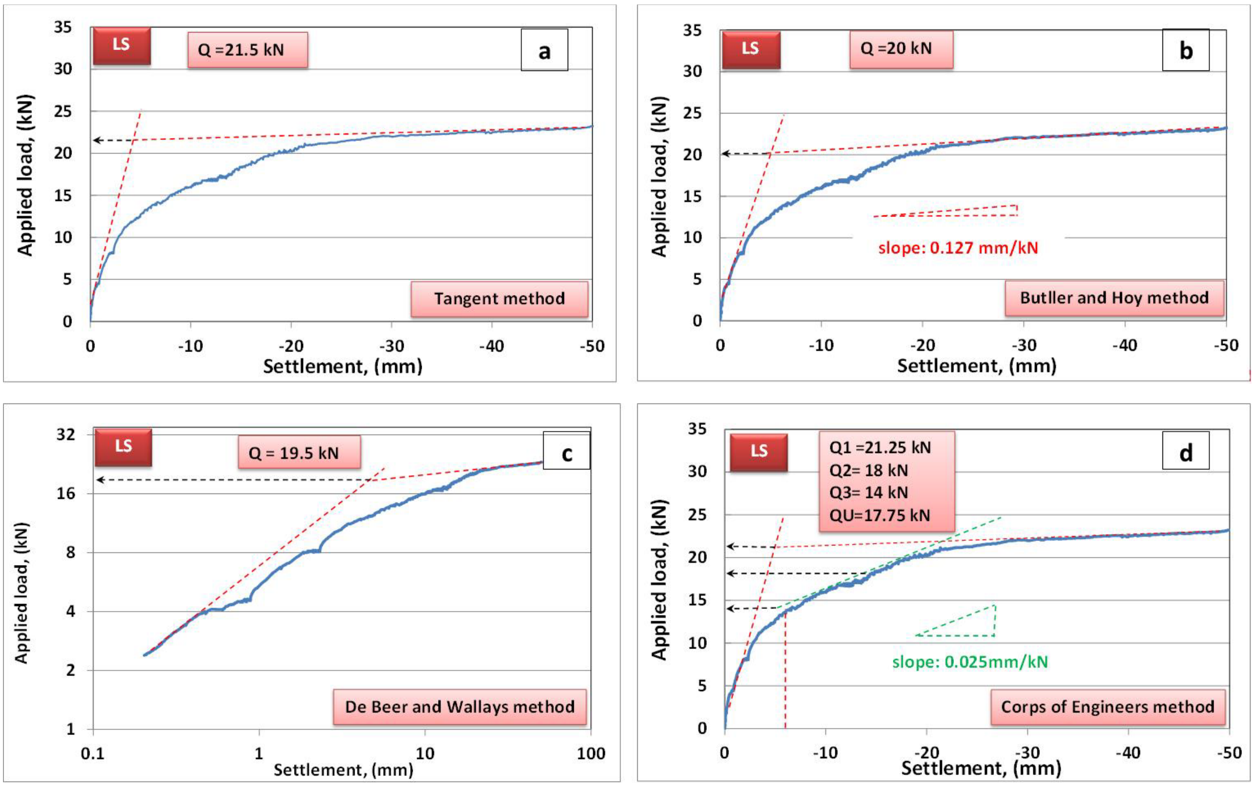

Figure 7. The use of graphical methods in determining the ultimate bearing capacity for the footing reinforced with single micropile in layered soil condition.

The ultimate load values at failure for the six loading instances were determined using the four aforementioned graphical methodologies, the results are listed in Table 2. It is observed that these values are differed to each other due to the difference in the methodology used to determine the point of failure for each method. Again, the maximum values of bearing capacity for the different six loading types are those values obtained from the tangent method followed by the other three methods [36, 37, 38] The variations in the ultimate capacities between the maximum and the minimum values are 50.0 %, 50.0 %, 35.1 %, 28.4 %, 21.1 %, and 23.5 % for the footing type of NLF, NLS, NLG, LF, LS, and LG, respectively. Therefore, taking the average ultimate load obtained from the four different approaches is the most sensible way to calculate the ultimate capacity. Table 2 lists the average ultimate load for each case. It is clear to notice that these values ranged between 11.25–24.63 kN. Taking into account that the square loading plate with ten centimeters a side, thus the bearing capacity ranges between 1125–2463 kPa. Fig. 8 shows the variation of ultimate bearing capacity for the studied cases. It is well noted that the bearing capacity of the foundation increases when the condition of the non-layered soil changes to the layered one. This finding is attributed to the improvement of the characteristics of the lower soil layers compacted with the modified Proctor energy (denser) compared to the properties of the upper soil layers compacted with the standard Proctor energy. Also, the results presented in Fig. 8 clearly show that the bearing capacity increases when the type of footing reinforced with a single micropile change to the case of a footing reinforced with a group of micropiles.

Table 2. Failure loads of footing determined by different graphical methods.

Methods	**Footing type**					
	NLF*	**NLS***	**NLG***	**LF***	**LS***	**LG***
Tangent method	13.50	15.75	25.00	20.75	21.50	26.25
Butller and Hoy, 1977	13.00	15.50	24.70	19.50	20.00	25.50
De Beer and Wallays, 1972	9.50	12.50	22.50	18.50	19.50	24.50
U.S. Army Corps of Engineering, 1991	9.00	10.50	18.50	16.16	17.75	21.25
Ave. load value at failure, (kN)	11.25	13.56	22.68	18.73	19.69	24.63

* Non layered soil with flat footing- NLF
Non layered soil with single micropile – NLS
Non layered soil with crоup micropile – NLG
Layered soil flat footing – LF
Layered soil with single micropile – LS
Layered soil with crоup micropile – LG

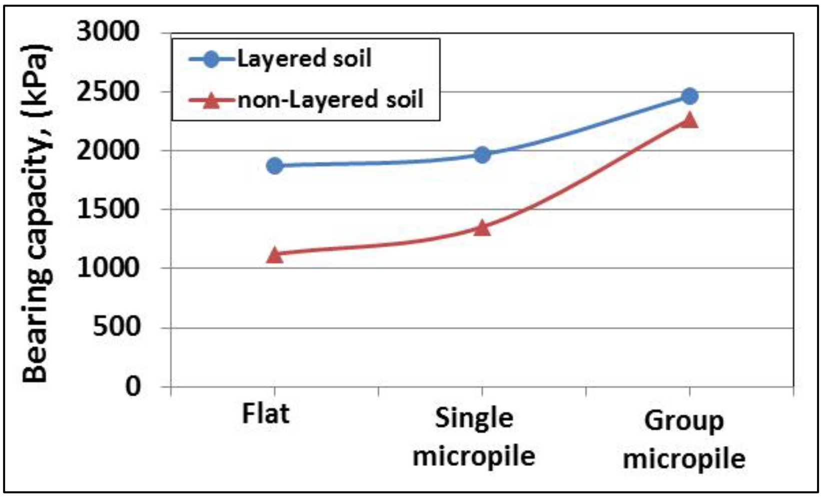

Figure 8. Ultimate bearing capacity of the loading plate at different conditions.

The next section deals with the bearing capacity ratio (BCR) and the percent of settlement reduction (PSR) when changing the state of the footing from non-reinforced footing to reinforced footing with a single micropile and/or with a group of micropiles, also when changing the state of the soil condition from non-layered soil to the layered one.

3.4. Bearing Capacity Ratio and Percent of Settlement Reduction

The bearing capacity ratio (BCR) is a dimensionless factor that can be used to examine the degree of improvement of the bearing capacity of footing at a certain condition. Equation (1) can be used to determine (BCR):

$$BCR,(\%) = \frac{q_{ult\cdot(reinf.)}}{q_{ult\cdot(non-reinf.)}}100, \tag{1}$$

where $q_{ult.(reinf.)}$ is the ultimate bearing capacity of loading plate reinforced with single micropile or group micropiles; while $q_{ult.(non-reinf.)}$ is the ultimate bearing capacity of non-reinforced loading plate (flat plat).

For example, the (BCR) of single micropile $\left(BCR_{S-M}\right)$ can be calculated as:

$$BCR_{S-M},(\%)=\frac{1969}{1873}\times 100,\quad BCR_{S-M},(\%)=1.05.$$

The BCRs for varying studied conditions are listed in Table 3. The data analysis shows that the BCR is more than 1 for all studied cases. Furthermore, for a given type of reinforcement, the BCRs decrease remarkably for the layered soil compared to the non-layered soil. Thus, it can be concluded that the BCR is strongly influenced according to soil condition during the test (i.e. layered soil or non-layered soil conditions). Also, the variation in the BCRs is clear when the type of footing reinforcement differs, the higher ratios belong to the footing reinforced with group micropiles.

Table 3. Calculated values of the bearing capacity ratio, (%).

Soil condition	Bearing capacity, (kPa)			Bearing capacity ratio, (%)	
	Flat	Single micropile	Group micropile	BCRS-M	BCRG-M
Layered	1873	1969	2463	1.05	1.32
Non-layered	1125	1356	2268	1.21	2.02

Again, the previous results showed that the reinforcement of the loading plate with micropiles reduces the settlement. To investigate these results distinctly, the percentage of settlement reduction (PSR) was calculated for each studied case, as shown in Fig. 9. Equation (2) was used to calculate the PSR:

$$PSR,(\%)=\frac{S_f-S_r}{S_f}100, \tag{2}$$

where S_f is the settlement of flat loading plate at a certain applied load while S_r is the settlement of the loading plate reinforced with micropile (single or group) at the applied load corresponding to S_f condition.

For the layered soil condition, the PSRs ranged between 35–20 % and 95–60 % for the loading plate reinforced with a single micropile and group micropiles, respectively. While in the case of non-layered soil, the PSR ranged between 30–20 % for the case of a loading plate reinforced with a single micropile. Again, the PSR is around 80 % for the case of a loading plate reinforced with a group of micropiles. It is noted from Fig. 9 that the highest PSR belongs to the layered soil compared to the non-layered soil condition.

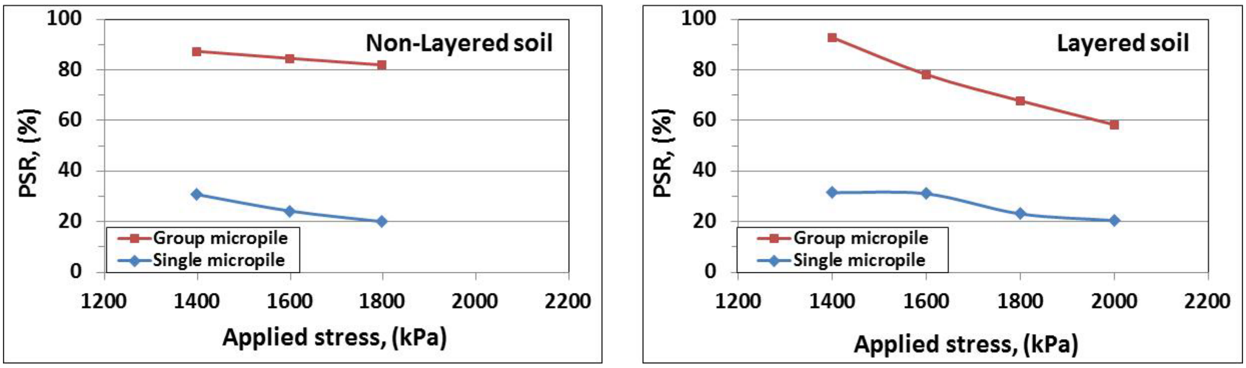

Figure 9. Percent of settlement reduction for footings tested in different conditions.

To give a discussion of the overall outcomes above, it can be said that the bearing capacity of the footing increases after being reinforced with a single micropile due to the creation of friction between the micropile and the surrounding soil. Additionally, the soil confinement on the one hand and the increase in the footing's stiffness on the other hand clearly have an impact on the BCR of the footing reinforced with a group of micropiles as opposed to the BCR of the footing reinforced with a single micropile. Another premise for interpreting the results is that the presence of group micropiles is likely to act as a senior pile. Also, the failure in the soil turns into a block failure type with a perimeter of the senior pile equal to about 15.6 cm (six micropiles x "0.6 + 2" the micropile diameter and the spacing between micropile, respectively). In this case, the interaction between this pile and the surrounding soil will increase, and thus the frictional surface area will increase. This, in turn, results in an increase in BCR and a decrease in PSR.

Regarding the effect of soil homogeneity, for the layered soil condition (the lower soil layers have a greater density than the upper soil layers), the results show that there is a clear increase in the footing bearing capacity or an improvement in the behavior of the load-settlement curves. It is very acceptable to explain these findings due to the increase in the angle of internal friction for the lower soil layers of high density compared to the upper soil layers of low soil density. However, it is possible to add to this interpretation the conclusion of [16]: the dense soil results in positive dilatancy during the load-settlement test, whereas the rule of the skin friction of micropile become crucial in the development of footing bearing capacity. On contrary, the soils with medium or low density will be exposed to negative or contractive dilatancy during the load-settlement test, and this will not lead to a significant increase in the bearing capacity of the footing, as is the case of dense soils.

4. Conclusions

The purpose of the current study is to investigate the effectiveness of micropiles in strengthening the soil and minimizing footing settlement of structures built on sandy silty soil from the eastern bank of the Tigris River in Mosul city - Iraq. The study is carried out using the experimental program on a laboratory-scaled model. The study was also interested in investigating the role of soil heterogeneity (weaker soil underneath by stronger soil) in the behavior of the load-settlement curves. The study's outcomes are as follows:

1. As a tool, the physical model was successful in identifying and describing the load-settlement curves for the six different loading scenarios performed in this study, including flat footing and footing reinforced with single or group micropiles in two different cases of soil homogeneity (layered and non-layered soil).
2. For all the cases studied, the footing's load settlement behavior under an axial compressive load is non-linear.
3. The use of micropiles as vertical reinforcement of the footing has a significant impact on the behavior of the load-settlement curve; an increase in the bearing capacity or a decrease in the settlement of the footing.
4. The BCR and PSR are two non-dimensional factors that are used to examine the improvement of the footing when reinforced with micropiles.
5. The role of the footing reinforcement in the non-layered soil is more obvious than in the layered soil. The bearing capacity of the footing reinforced with group micropile embedded in non-layered soil is 2268 kPa which is equivalent to BCR = 202 % more than non-reinforced footing. Whilst, the footing reinforced with a group of micropiles but embedded in layered soil has a bearing capacity of 2463 kPa or 132 % more than the footing without reinforcement BCR = 132 %.
6. In contrast to layered soil, the role of footing reinforcement is more noticeable in non-layered soil. The bearing capacity of the footing reinforced with group micropile embedded in non-layered soil is 2268 kPa which is equivalent to 200 % more than non-reinforced footing BCR = 202 %. Whilst, the footing reinforced with a group of micropiles but embedded in layered soil has a bearing capacity of 2463 kPa or 132 % more than the footing without reinforcement BCR = 132 %.
7. In the case of non-layered soil, the presence of the strong soil layers under the weak soil layers increases the bearing capacity from two points of view: the first is that the increase in the density of the strong soil layers increases the angle of internal friction and thus increases the bearing capacity of the footing. The second one is that the presence of the micropiles in the strong soil layers leads to an increase in the confinement of the soil surrounding these micropiles, and thus the occurrence of a positive dilatancy for the soil that has a high density, which increases in the bearing capacity. This is not the case in low-density soil layers which are accompanied by negative or contractive dilatancy during the load-bearing test.

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