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Bearing Capacity of Ring Footing on Stabilized Clay with Sand Trench- Stone Pile Combination

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Abstract

Ring footings are usually used for symmetrical buildings like silos, chimney, and oil storage. One of the most important problems are to construct these footings on marine deposits of very soft clay which extends in Egypt in the northern of the delta and the north of the Suez gulf. Replacing the soft clay soil with granular mixture is the most famous and cheapest techniques to increase the bearing capacity of these soils. The aim of this research is to introduce a new technique using sand trench and stone piles to reinforce the soft clay below the ring foundation. Laboratory investigation has been performed to study this combination. The effect of different factors such as the width, the thickness of sand trench, and the presence of stone piles below it have been examined. Results showed that the utilizing sand trench-stone piles combination decreases the settlement and increases the footing bearing capacity. Dimensions of sand trench and stone pile appeared to be an important factor in improving ring footing behavior on soft clays.

Keywords: *Bearing Capacity, Ring Footing, Sand Cushion, Stone Piles, Soil Improvement.*

1. Introduction

Soft clay deposits have high compressibility and low shear strength. Shallow footings, when built on these soils, have a low load-bearing capacity and undergo large settlements. One of the appropriate method to improve bearing capacity of such soil is placing a layer of compacted sand over it. The depth of the replaced sand depends on the required bearing capacity and the allowable settlement. Sometimes this technique leads to great heights of soil replacement and hence excessive cost and effort.

Several researchers such as (Meyerhof [1]; Hanna [2-3] and Hanna and Meyerhof [4-5]), study the behavior of shallow foundation on layered systems, concerning the case in which a sand layer overlies a soft clay layer.

The two major criteria that control the design of shallow foundations on cohesion less soils are the bearing capacity of the soil beneath the footing, and settlement of the foundation. However, settlement usually controls the design process rather than bearing capacity [6].

An approximate method to estimate the vertical surface displacements of a multi-layer system due to a uniform load on the surface was mentioned by [7]. It was assumed that the upper layer may be replaced by an equivalent thickness of the lower material. A general shear type of failure surface under the footing was assumed by [8]. The failure zone consists of four parts: 1 - Rankine active zone, 2 - Mixed transition zone, 3 - Transition zone, 4 - Passive zone. The theoretical ultimate bearing capacity of the foundation was determined by using the upper bound limit analysis theorem.

Brown and Meyerhof [9] investigated the ultimate bearing capacity of foundations resting on clay subsoil’s for the cases of a stiff layer overlying a soft layer, and the soft layer overlying a stiff layer. The studies have been based on model tests using circular and strip footings, and using a range of layer thicknesses and clay strengths. The results of the investigation are summarized in charts. This may be used in evaluating the bearing capacity of layered clay foundations. The problems contain many variables, and the limitation of the study may be seen from the following points, which set forth the scope of the experimental work. All studies were carried out in terms of undrained shear strength of the clay, using total stress analyses. Studies were confined to surface loadings, using rigid strip and circular footing with rough bases. Only one type of clay was used. Therefore, although the strength of the clay was varied, the deformation properties remained constant.

1.1 Reinforcement using sand trench replacement

The use of granular trench in the construction of shallow foundations founded in weak saturated clay was studied by S.I.Shalaby [10] and M.A.Sabry [11]. The solution of such problem has been proposed mainly based on model studies. All the obtained results indicate that the ultimate bearing capacity of a strip footing resting on a granular trench constructed in weak saturated clay is much higher than the obtained for the layered system of the clay itself.

The ultimate bearing capacity of footing on sand trench inside weak clay can be expressed by punching shear coefficients.

1.2 Reinforcement with Stone Pile.

The estimation of the bearing capacity of stone pile reinforced weak soil has been reported in many earlier studies. However, the design and estimation of the bearing capacity in these studies are based mostly on plane strain semi-empirical methods (e.g., Aboshi et al. [12]; Hughes et al. [13]; and Madhav et al. [14]). Eissa et al. [15] proposed a graphical model to estimate the ultimate bearing capacity of stone pile reinforcing system. The bulging failure mechanism was adopted in which the stone pile is assumed to displace laterally against the surrounding clay in an outward direction until passive failure occurs, Fig.1. Concurrently, the stone fails in an active failure mode. The ultimate bearing capacity is then determined based on the knowledge of the radial stresses and the assumption that the stone material fails under active conditions forming a bulge failure.

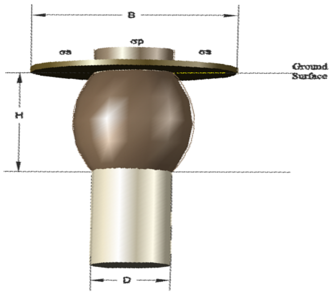

Fig. 1 A Typical Pattern of Bulging Failure Mode.

Many previous studies estimated the stress the stone pile can carry as well as the stress concentration ratio between stone pile and the surrounding soil. Some of these studies were based on theoretical approaches while others based on empirical and numerical analysis. Aboshi et al [12] ignore the change in the applied load diameter, also overestimates the stress concentration ratio for diameter ratios less than 2. Aboshi's approach assumed that the applied load entirely covers the passive zone.

Bouassida et al.[16] presented a study for predicting the enhancement in bearing capacity due to the reinforcement of weak soil by using single granular piles by considering the soil equivalent method. [16] doesn't take into consideration the bulging effect, it was considered that the whole area beneath the applied load for either the pile material or the surrounding soil is in active state.

Prakash et al. [17] modified Hughes approach in the case of clay if the diameter of the applied load is larger than the diameter of the pile.

In this study a combination of both sand trench and stone piles was used in stabilizing soft soil. Where the technique of using vertical reinforcement in the form of stone piles that are driven under foundation was used to improve the load bearing capacity, controls the horizontal movement of soil under the footing and provided a confinement for the weak clay soil.

This adopted technique is done by partial replacement of soft soil via well compacted sand trench that confined with the same weak clay soil (as a replaced big sand column).

Therefore, the main objective of this research is to address the aspect of both the bearing capacity improvement and settlement reduction through using both local soil replacement of soft soil and the use of stone pile soil system. This local stabilization is used only for decreasing both the amount of replaced soil and compaction effort that is required for replacement process.

The utilization of stone piles beneath the sand trench replacement layer on footing pressure-settlement relationships was investigated and evaluated. The experimental results are presented and compared against several studied parameters. This paper examines the effect of modifying the soil replacement layer to be a trench inside the soft clay layer. To accelerate the improvements in soft clay behavior granular stone piles were driven at the mid width of the ring footing at spacing equals to three times pile diameter and extended to a depth of ten times pile diameter. The study presented herein describes the effect of varying the dimensions of the trench replacement sandy soil beneath ring footing above a weak clay deposit on the load-settlement behavior.

2. Experimental Work

2.1 Experimental Setup

The experimental setup consists of a loading frame, a tank, a model footing, and the stress and settlement measuring devices. Fig. 2 shows a schematic view of the experimental model apparatus used in this study. The container is a part of steel pipe of inner diameter of 76.2 cm, 1.27 cm thickness, and 83.75cm height. The container was designed to accommodate the used ring footing with outer diameter of 200 mm, so that the tank boundaries exert minimum effects on the stress and strains developed in the soil [18].

A loading frame provided with a hydraulic jack was used in applying the load on the model footing.

The ring footing is modeled by a rigid circular steel plate of 25 mm thickness with inner diameters of 100 mm. and outer diameter of 200 mm. In order to simulate the roughness of the actual footing, the bottom of the model footings were made rough by gluing sand paper.

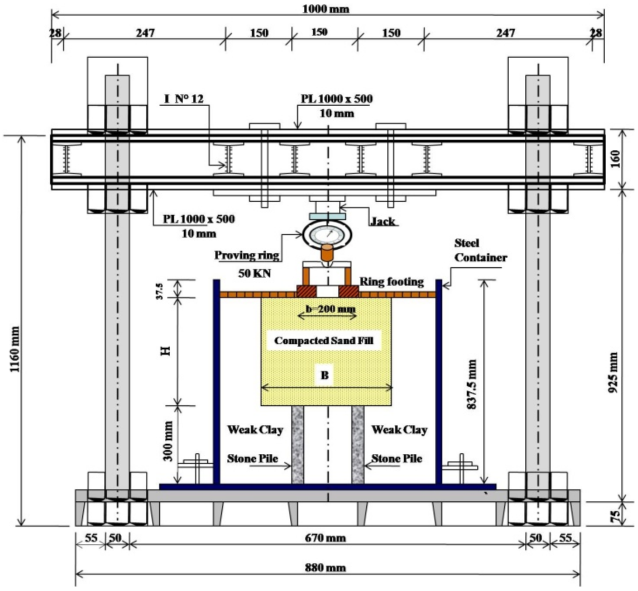

Fig. 2 Schematic view of the experimental model apparatus

The loading system is designed to be rigid and capable of sustaining high stresses involved without suffering from excessive deflections. A system with a recess made at its center to accommodate a ball bearing through which vertical loads is applied to the ring footing and to ensure that no moment is applied to the footing model. For minimizing the effect of side friction, lubricating material was used at the contact surface of soil with model container. The magnitudes of the applied loads were recorded with the help of a sensitive pressure gauge and proving ring of 50 kN capacity. A dial gauge with accuracy 0.01 mm and maximum travel 25 mm was used to measure the correct vertical settlement of the footings for each increment of applied load.

2.2 Test Materials

The materials used in this study are clay, sand, and gravel having the following properties:

Clay: The clay used in this investigation contains about 8% sand, 38% silt and 54% clay. The specific gravity was 2.72 and its natural water content was 33% the liquid limit, plastic limit, and plasticity index were 79 %, 29 % and 50%, respectively, and this type of clay was classified as clay with high plasticity (CH) according to Unified Classification System.

Sand: The sand used in this study was air-dried medium to coarse angular silica sand.

Gravel: The fine gravel used in this investigation was dry, siliceous and particle size 2.25mm to 10 mm.

The physical and mechanical properties of tested sand and gravel are summarized in Table 1.

2.3 Sample Preparation

The clay was thoroughly mixed during model tests at water content of 60 %, a period of 3 days was allowed for curing before compaction in model tank. By applying a gradually static uniform pressure of 40 kN/m^2 a normally consolidated bed of clay can be obtained as presented by El Sawwaf [19]. The pressure was kept for 48 hour then gradually released in 2 hour. The shear strength for the soil was obtained through Pocket Vane Shear Tester. This procedure was adapted to maintain the clay strength within a limited range for all footing tests. The degree of saturation of the compacted clay bed varied between 96.5% and 99.8%. Since 98% saturation was achieved, the clay might have been treated as fully saturated which meant that ø = 0 concept could be applied in the analysis of the result.

Table 1 Properties of used sand and gravel.

Properties	Sand	Gravel
Size in mm	0.075to 4.75	2.25- 10.0
% Passing N 200 US sieve	1.1	0.0
$D_{10\%}$ (mm)	0.33	3.1
Uniformly coefficient (Cu)	5.45	1.94
Curvature coefficient (Cc)	0.95	1.4
Max. dry density (KN/m^3)	18.6	19.2
Min. dry density (KN/m^3)	14.7	17.4
Relative density during tests	70%	70%
Specific Gravity (Gs)	2.62	2.68

The compacted sand soil trench was placed uniformly and tamped manually to reach an average density of 17.2 KN/m^3 which corresponded to medium state. The fine gravel particles was placed after drilling the pile using a drilling device in layers and tamped manually to reach a backed state.

2.4 Experimental Procedure

The model set up shown in Fig.3 was prepared by placing the lower soft clay layer in the testing mould in layers not more than 5.0 cm thickness and compacted to reach the required density. The compaction was done statically through steel plate of the same diameter of the mould. Pocket Vane Tests were done on each layer to make sure that its strength is less than 5.0 kN/mm^2. The top surface of the compacted clay in the container was sealed with a damp cotton layer and left for a period of 7 days for curing. Once the compacted clay layer was cured, the wooden block placed during compaction of soft clay layers to form sand trench was removed, the stone piles were driven and filled with fine gravel, then sand forming the trench replacement was powered in 5.0 cm thick lifts for each lift, the amount of sand needed to produce the desired dry density was weighted out and placed in the trench void, then leveled out and tamped to form the proper depth. Compaction was carried out very carefully so that the prepared soft clay did not get disturbed. After that the model footing was centrally placed. The influence of the soil above the level of the footing was replaced by a uniform surcharge (q) of 20 KPa.

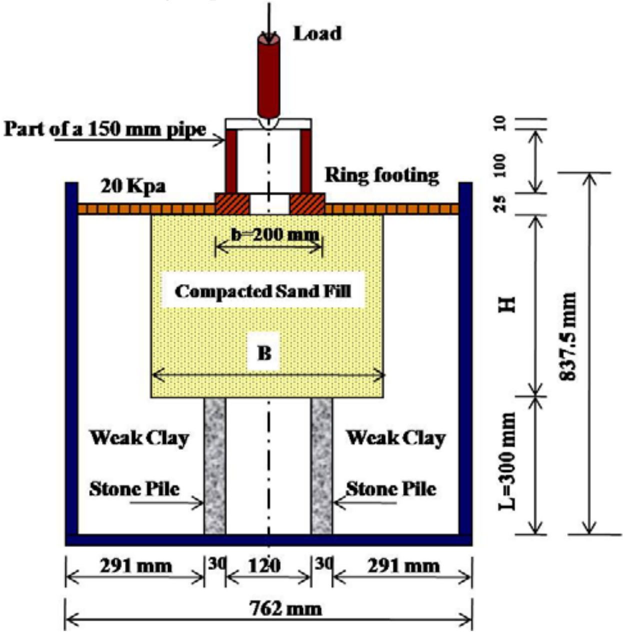

Fig. 3 The Model Setup

A manually operated hydraulic jack was used to apply loads of the footing in small increments. A proving ring connected to the jack and the footing measured loads. In order to record the correct vertical settlement of the footings for each increment of applied load two sensitive dial gauge were used and their average was taken. Measurement was continued until the entire load settlement curve to failure was obtained.

The load was applied in small increments until reaching failure and maintained for at least 5 minute till all movements had ceased based on recorded deflection readings. The ultimate bearing capacity in any test was defined as the load corresponding to the point where the load settlement curve becomes relatively steep and straight [6]. Based on the reading of the proving ring and dial gauge, stress-settlement curve were computed and plotted.

2.5 Testing program

A series of loading tests were carried out for ring footing with and without stone piles resting on partially replaced soft clay by sand. The effect of dimensions of sand trench and stone pile on the stress-settlement behavior and ultimate bearing capacity of ring footing resting on weak clay layer, was studied under axial load. The parameters studied are; Width of sand trench B/b, depth of sand trench H/b,. All experimental work stops at H/b=2 and B/b=2 for practical purposes.

Table 2, presents the different parameters and the testing program. A total of 19 laboratory tests were performed at the same relative density of 70% for sand trench layer.

Table 2 Laboratory test program

Depth of replacement sand trench (H/b)			Width of replacement sand trench (B/b)		
1.0	1.5	2.0	1.0	1.5	2.0

As shown in Fig.4 in all tests four holes of diameter 30 mm at equal spacing extending 300 mm below sand trench were drawn and filled with fine gravel to simulate stone piles beneath ring footing.

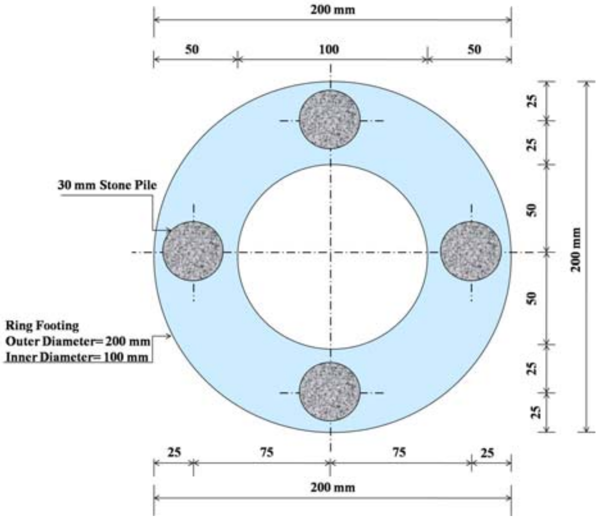

Fig. 4 Arrangement of stone piles below sand trench.

3. Results and discussions.

An initial reference test was performed for axially loaded ring footing on the top of weak soft clay layer without any improvement. A typical stress – settlement relationship was shown in fig. 5.

The ultimate load is defined as the point at which the slopes of the pressure-settlement curve first reach zero or minimum value. These criteria required that the footing test be carried to large displacement, exceeding 25% of the foundation size [18].

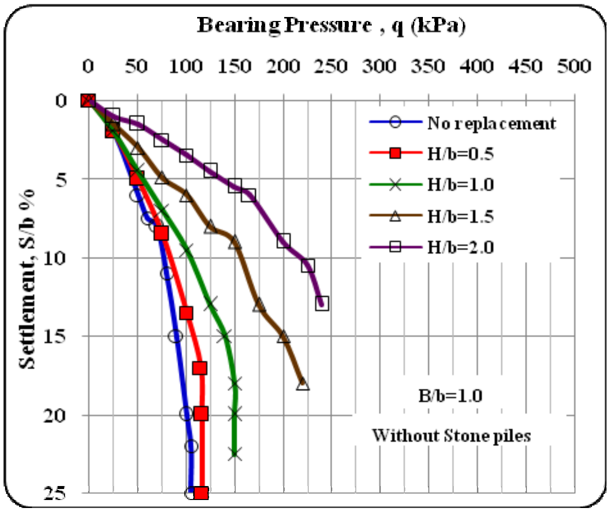

Fig. 5 Variation of bearing pressure, q versus normalized settlement for different replaced sand trench depth for ring footing without stone piles.

The studied variables were combined with footing diameter b, into a dimensionless parameter. The terms Bearing Capacity Ratio (BCR) and Settlement Reduction Factor (SRF) are used for convenience to interpret the test data. The increase in maximum vertical pressures is defined as Bearing Capacity Ratio, (BCR).

$BCR = q_r / q_o$ (1)

Where:

Q_r = The ultimate vertical pressure at any test.

Q_o = The ultimate vertical pressure at the initial condition without any improvement.

The decrease in maximum vertical settlement is defined as Settlement Reduction Factor (SRF). (SRF) is the ratio of the maximum vertical settlement under the footing at any case (S_r) to the settlement of footing on soft clay layer corresponding to its ultimate bearing capacity, (S_o).

$SRF = (S_o-S_r)/S_o*100(\%)$ (2)

3.1 Effect of partial replacement with sand trench and stone piles

In order to investigate the effect of partial replacement of weak clay soil with sand trench, Fig. 5 is presented. Fig. 5 shows the variation of bearing pressure (q) and normalized settlement, S/b for the ring footing without stone piles resting on partially replaced soft soil as a replaced sand trench beneath the footing at different sand trench depth, H/b ratios. From the examination of the results plotted in Fig. 5 it is clear that the use of sand trench as a partial replacement of soft clay, highly improves and modifies the load bearing capacity at the same settlement ratio. Whereas, the stress–settlement relationship when using stone piles under the ring footing on partially replaced soft clay for different sand trench thickness is shown in Fig. 6. Fig.5 and Fig. 6 show the results for the case of (B/b = 1).

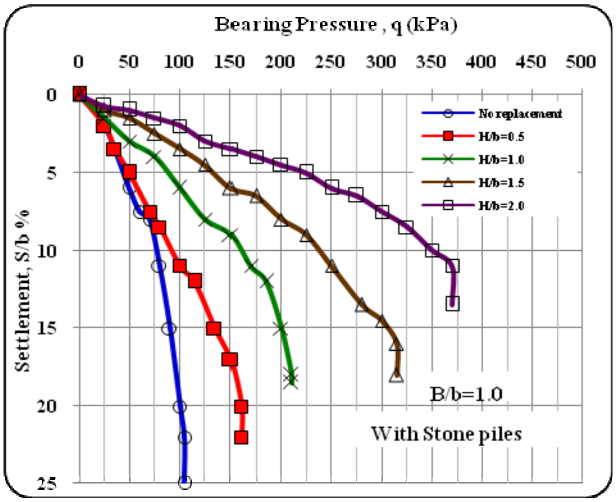

Fig. 6 Variation of bearing pressure, q versus normalized settlement for different replaced sand trench depth for ring footing with stone piles.

From the study of these figures it can be seen that the presence of stone piles with the replaced sand trench noticeably improves the bearing capacity of the footing as well as the stiffness of the foundation bed. The vertical stone piles are acting as a confining cell to the soft clay surrounded by stone piles, due to this confining both the vertical and the horizontal strain underneath the footing decreases as compared with the case of the absence of stone piles. Stone piles also controls the settlement of the footing/soil system. At high H/b ratios the soil surrounding the sand trench induces a confinement pressure in the lower zones. From the observation of the failure mechanism at the end of tests it is conceivable to conclude that the actual bulging occurs at the higher stress concentration which indicates minimum surrounding soil resistance.

3.2 Effect of replaced sand trench depth

Fig. 7 shows the variation of bearing capacity ratio, BCR with normalized replaced sand trench depth (H/b) for different sand trench width ratios (B/b) for the ring footing with or without stone piles under the replaced soil. From the meditation of the results shown in Fig. 7 it is clear that the bearing capacity ratio (BCR) is gradually increased with the increase of the replaced depth.

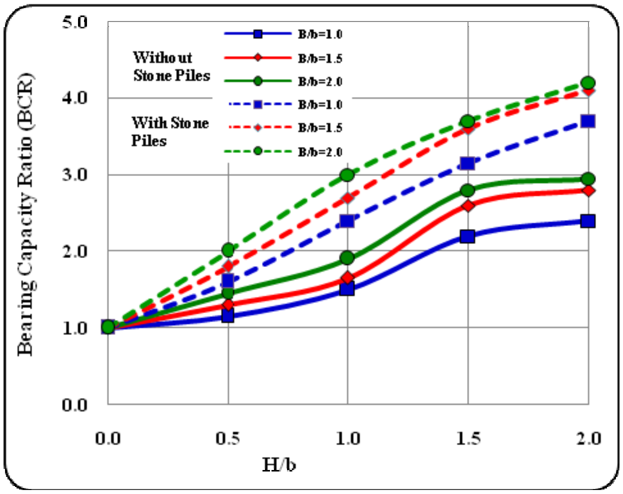

Fig. 7 Variation of the BCR with different replaced sand trench depth for different sand trench width for footing with and without stone piles.

A significant increase in the bearing capacity ratio is observed at (0.5 < H/b <1.5) when no stone piles are installed and observed at (H/b> 0.5) when stone piles are used. The rate of increase in the bearing capacity ratio reaches a minimum values at H/b>1.5 in case of no stone piles. Also, the degree of improvement on BCR mainly related to sand trench depth rather than sand trench width . As the depth of sand trench increases the amount of confinement of replaced sand is increased as a result the bearing capacity is increased.

3.3 Effect of replaced sand trench width

From the study of the results shown in Fig. 8 it is noticed that as the width of sand trench increases the bearing capacity ratio is increased. Also, the presence of stone pile has a great effect in increasing the degree of improvement compared with case of footing on sand trench without stone piles. The presence of sand trench with B/b = 2.0 increases the bearing capacity to 1.9 times of initial ultimate bearing capacity of soft clay at H/b= 1 and 2.95 times at H/b = 2. Alternatively, at the case of the presence of stone piles beneath the sand trench with B/b = 2.0, the bearing capacity is increased by 3.0 times value at H/b = 1 and 4.1 times at H/b = 2.0. This variation in the degree of improvement in the two cases was related to the bulging behavior of unconfined condition. This can also confirm the effectiveness of stone piles as a confined tool.

It is evident from the results plotted in Fig. 8 that the effect of increasing B/b ratios for the same H/b ratio in the increase in BCR is nearly small which indicated that the increase in depth of the sand trench is more effective than increasing width of sand trench.

The meditation of the results shown in Fig.8 shows that the best ratio of the used B/b ratio is 1.5, after that the rate in increasing B/b ratios is small.

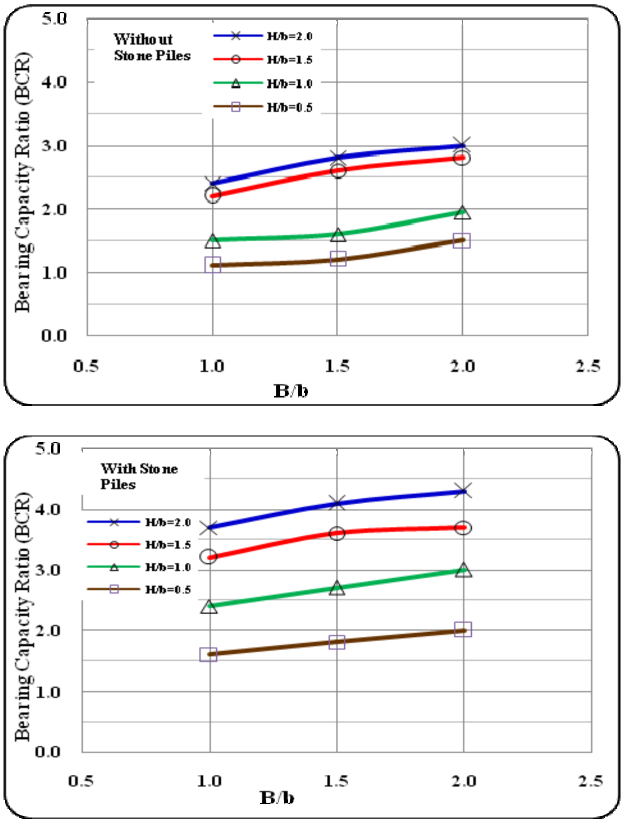

Fig. 8 Variation of the BCR with sand trench width for different depth with and without stone piles.

3.4 Effect of the presence of stone piles below sand trench

It can be seen from the study of Fig. 7 that the installation of stone piles with the replaced sand trench noticeably improves the bearing capacity of the ring footing as well as the stiffness of the foundation bed. The vertical stone piles is acting as a confining cell to the inside soft clay soil beneath the sand trench and effectively decreases both the vertical and the horizontal strain underneath the footing compared with the other case. It also controls the settlement of the footing/soil system.

As the failure approaches in tests carried out on footing with stone piles, the replaced sand inside the trench behaves as one unit and behaves similar to deep foundation. Also from the study of the results shown in Fig. 8 it is clear that the presence of stone piles beneath the sand trench with B/b = 2.0, the bearing capacity is increased by 3.0 times value at H/b = 1 and 4.1 times at H/b = 2.0. This variation in the degree of improvement in the two cases was related to the bulging behavior of unconfined condition. This can also confirm the effectiveness of stone piles as a confined tool.

3.5 Settlement reduction due to soil improvement

The relationships between the settlement reduction factor, SRF in percentage and the replaced depth for ring footing with and without stone piles are presented in Fig. 9.

It has been found that the existence of sand trench below the footing decreases the amount of settlement of the system. The percentage reduction in settlement was affected by both replaced sand trench depth and the presence of stone piles at the center of the ring footing as distinctly explained in Fig. 9. In this figure nonlinear correlation is found exist because the replaced sand trench when subjected to footing load compressed until bulging induced. Moreover, as the depth of sand trench increases the percentage reduction in settlement increases. This is due to the shear stress mobilized at the perimeter of sand trench.

From Fig. 9 it is clear that, with increasing the sand trench thickness the vertical settlement decreases rabidly until reaching a ratio (H/b) equal to 1.5, the settlement becomes almost the same. This reduction of vertical settlement is due to the increase of sand height that increases the frictional resistance which causes more improvement of the vertical stress distribution. In addition, the compression of sand is less than that of original soil which is clay.

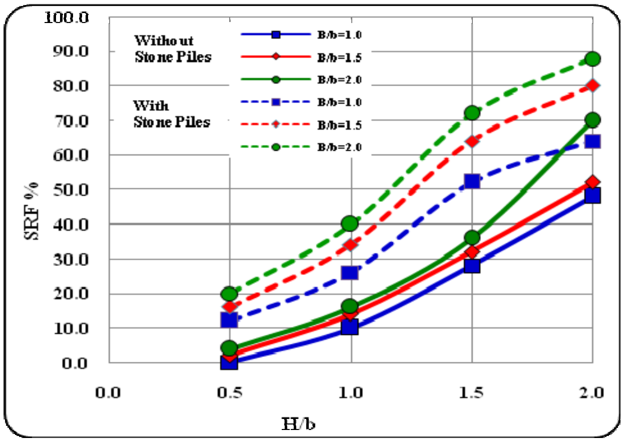

Fig 9. Effect of sand trench depth for different sand trench width on the settlement reduction factor, SRF% with and without stone piles.

The settlement reduction factor, SRF % is reached to 10 % for footing on replaced sand trench without stone piles at (H/b = 1, B/b=1). This value is increased according to sand trench thickness, wherever, at (H/b = 2) the SRF % reaches 48% for the same replaced sand trench width (B/b = 1) as distinctly shown in Fig. 10. It also noticed that the percentage reduction in settlement SRF% is greatly increased with the existence of stone piles with sufficient number compared to other case. This also, again justifying that the use of confined partially replaced sand trench with stone piles is more effective in increasing the foundation stiffness, controls the horizontal and vertical movement underneath the footing, and demonstrates that the footing and sand trench confined by surrounding soft clay soil acted as a rigid one unit behave similar to deep foundation.

The SRF% at B/b = 2 reached to 40 and 88 for (H/b = 1 and 2, respectively). These values are more than those of footing without stone pile confinement. For that reason, in cases where structures are very sensitive to settlement, weak soil confinement by stone piles can be used to obtain the same allowable bearing capacity at a much lower settlement.

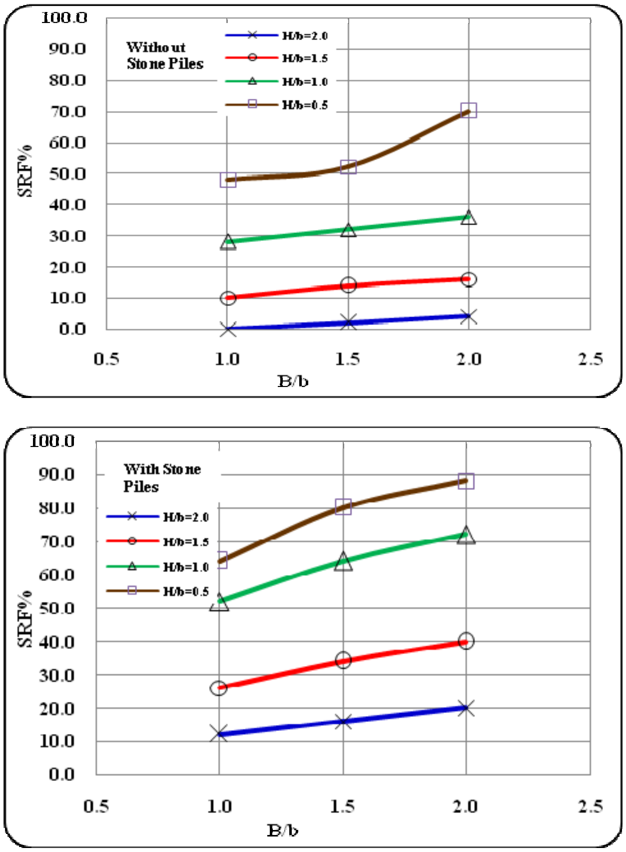

Fig. 10 Effect of sand trench width for different sand trench depth on settlement reduction factor, SFR % with and without stone piles

4. Conclusions

The use of a combination of stone piles and sand trench instead of using complete sand replacement cushion above weak soft clay soil was investigated experimentally using model ring footing. Based on the results presented and discussed in this investigation the following conclusions can be drawn.

- The use of the adopted technique can substantially modify the stress displacement curve of the ring footing rested on soft clay layer, significantly decreases the settlement and increases the bearing capacity.
- The improvement of bearing capacity is remarkably increased using both partially replaced sand trench with or without stone piles.
- Increasing the dimensions of the replaced sand trench causes a decrease in the stresses transmitted to the underlying clay layer and increases the uniformity of stress distribution on the bottom of clay layer.
- The confinement induced due to the presence of stone piles has a considerable effect in decreasing the vertical settlement.
- The percentage reduction in settlement is highly depended on both sand trench dimensions and the presence of stone piles.
- In cases where structures are very sensitive to settlement, stone piles replacement can be used to obtain the same allowable bearing capacity at a much lower settlement.
- The replaced sand soil block inside the trench behaves as a deep foundation or one unit. Therefore, the bearing capacity failure mechanism of normal footing on soft clay is modified from excessive settlement pattern to general bearing capacity failure.
- Critical depth and width of replacement sand trench is 1.5 times footing width, after that increasing depth or width of sand trench has small effect on increasing bearing capacity.
- BCR remain nearly constant after using a sand trench of thickness exceeding twice of the width of the ring footing.

Appendix 1: Notation

The following symbols are used in this paper

b : Footing outer diameter ; cm
B : Width of sand trench; cm
H : Thickness of sand trench; cm
q : Uniform surcharge ; KPa
BCR: Increase in maximum vertical pressure
S : Maximum vertical settlement; mm
SRF : Settlement Reduction Factor; %

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