Behavior of Circular Footing under Axial Loads on the Top of a Cemented Sand Layer Underlain by a Weak Sand Layer

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Abstract: One of the most common methods for founding on expansive soil is the use of sand replacement cushion with great depth to minimize the harmful effect of expansive soil. In some cases the sand cushion failed to achieve the required compaction ratio needed to support the applied loads. The use of a poorly cemented sand layer beneath foundations is commonly used instead of re-compaction of the sand replacement layer. The objective of this research paper is directed towards investigating experimentally the behavior of cemented sand under the effect of circular footing on weak sand cushion. A laboratory experimental work program was carried out using model circular footing to investigate the effect of cemented sand on the performance of circular footing on loose sand cushion. The main parameters affecting the bearing capacity and settlement of the cemented sand are studied in this investigation. These parameters include footing diameter, thickness of both cemented layer and loose sand cushion. The stress-settlement relationships are used to specify the ultimate footing bearing capacity. It was found that the presence of a top rigid layer significantly increases the bearing capacity and decreases the settlement of the footing. The critical depth of cementing upper sand layer after which increasing depth of cementation has no effect on increasing bearing capacity was determined.

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Keywords: Bearing capacity, Bearing capacity ratio (BCR), Settlement reduction factor (SRF), Replacement layer, Soil cement, Circular footing, and Layered soil.

1. Introduction

When sand cushion used for founding on expansive soil failed to achieve the required bearing capacity to support the applied loads , the bearing capacity of the replacement soil is very low and compressibility is high. In such cases to increase bearing capacity the existing weak soil is removed up to a shallow depth and replaced by the same sand reinforced with cement. Mixing sand with cement to form what is called sand-cement had proved its effectiveness, and economy as a base material for pavements, and many other applications as a slope protection, embankments and dams construction. 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 [10]. The geotechnical literature has included several methods, both theoretical and experimental, to predict settlement of shallow foundations on cohesion less soils. However in the case of stratified soil profiles , the effect of layering must be taken into account. 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 [9].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 [7]. 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. The problem of bearing capacity of layered soil has been studied among others by [1, 2, 3, 4, 5, and 8].This paper examines the effect of cementing the top portion of soil replacement above strong expansive soil on the load-settlement behavior of circular model footing. The experimental results are presented and compared against several parameters.

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, Figure 1. The container is a part of steel pipe of inner diameter of 76.2 cm, 1.27 cm thickness, and 73.75 cm height. The container was designed to accommodate the footing of variable diameter so that the tank boundaries exert minimum effects on the stress and strains developed in the soil [12]. A loading frame provided with a hydraulic jack was used in applying the load on the model footing. The footing is modeled by a rigid circular steel plate of 2.5 cm thickness with different diameters: 2.5,5 and 7.5 cm. In order to simulate the roughness of the actual footing, the bottom of the model footings were made rough by gluing sandpaper.

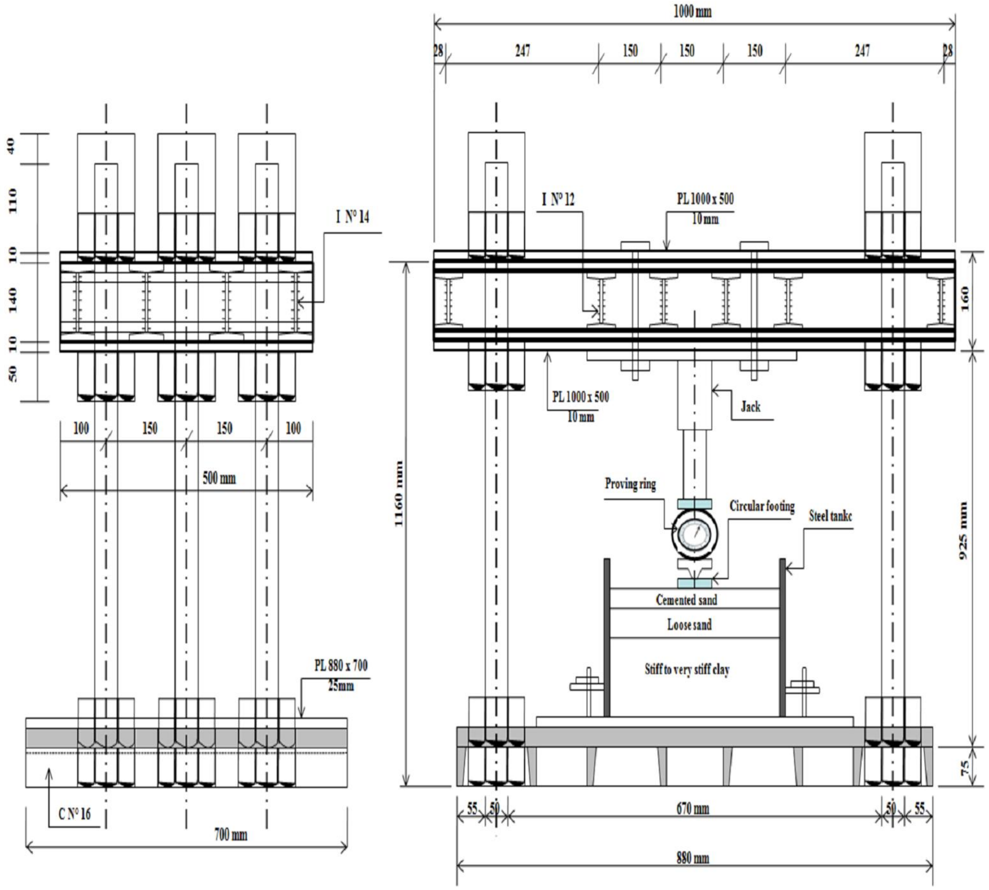

Figure 1. The loading frame, the tank.

The loading system is designed to be rigid and capable of sustaining high stresses involved without suffering from excessive deflections. A recess is made into the center of the footing model to accommodate a ball bearing through which vertical loads are applied to the 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 load applied.

2.2 Test Materials

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

Sand: The sand used in this study was air-dried medium to coarse angular silica. The grain size distribution showed a uniformity coefficient equal to 2.5. The specific gravity of the particles was found to be 2.64. Laboratory tests on this sand indicated maximum and minimum void ratios of 0.886 and 0.600, corresponding, respectively. Triaxial compression tests with volume change measurements were performed on air-dry samples at an initial relative density of 70%. This, same relative density was achieved by vibration in the model tests described in the next section. The mean angle of internal friction was found to be 40.8°.

Cement: The used cement in the laboratory testing is commercially available and known as Kawmeya Portland cement, produced by Kawmeya Company at Toraa – Cairo.

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.

2.3 Sample Preparation

The clay was mixed during model tests at water content of 35% a period of 3 days was allowed for curing before compaction in model test. This procedure was adapted to maintain the clay strength within a limited range for all footing tests. The bulk density as obtained in all tests varied between 19.0 KN/m^3 and 19.4 KN/m^3. with water content of 31.1 % and 30.3 %, respectively. The degree of saturation 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, therefore, the shear strength was measured by conducting unconfined compression tests on a sample 76 mm long and 38 mm in diameters, trimmed immediately after each footing tests from a block of clay cut from the container . The average undrained shear strength was found to be 18.8 ± 3.5 kN/mm^2.

The weak sand soil layer was placed uniformly using a funnel at a predetermined height to reach an average density of 15.66 KN/m^3 which corresponded to medium to loose state.

Based on the results of modified proctor compaction tests, the required amount of dry sand and cement were exactly weighted, the dry sand and cement were thoroughly mixed. The sufficient water was added to produce the required optimum moisture content for the mixture. Based on a preliminary laboratory tests, optimum values of cement is 6% of dry sand weight.

2.4 Experimental Procedure

The model test shown in fig.2 was prepared by placing the lower clay layer in the testing mould in layers not more than 2.5 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 penetrometer tests were done on each layer to make sure that its strength not less than 17.5 kN/mm^2 or re-compaction must be done. 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, top sand layer 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 container using a funnel. The soil was then leveled out and tamped to from the proper depth. The sand cement mixture required to form the top cemented sand layer was left 5 minute after adding the required water to produce the optimum moisture content to achieve partial pulverization, then placed and leveled in the test tank in layers. Each layer was compacted by a steel hammer to reach the desired unit weight of the mixture. The mixture was left to be air dried for 72 hours before testing. 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 KN/m^2. 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.

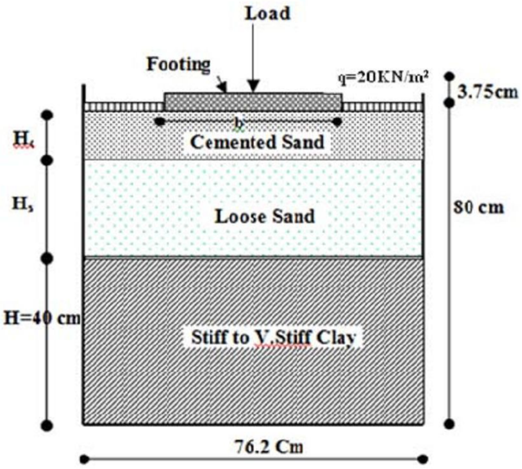

Figure 2. Experimental model setup

Equal increments of load were applied 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 [6,11]. Based on the reading of the proving ring and dial gauge, stress-settlement curve were computed and plotted.

2.5 Testing program

To study the effect of adding cement on the stress-settlement behavior and ultimate bearing capacity of circular footing resting on the top of weak sand layer over laying a strong clay layer, a series of laboratory model footing tests under axial loads were performed. The parameters studied are; footing diameter b, thickness of loose sand layer Hs/b, thickness of cemented sand layer Hc/b. All experimental work stops at Hs/b=3 and Hc/b=1.5 for practical purposes. Table 1, presents the different parameters and the testing program. A total of 27 laboratory tests were performed at the same relative density of 70% for top sand layer overlaying a stiff to very stiff clay layer.

3. Results and discussions

An initial set of reference tests was performed for axially loaded circular footing on the horizontal top of a loose sand layer above an extended stiff to very stiff silty clay layer. A typical stress–settlement relationships for footing with 2.5, 5.0, 7.5 cm diameter are shown in figure 3. The ultimate load is defined as the point at which the slope 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 [12].

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 Factor (BCF). BCF = $[(\sigma_1 - \sigma_o)/\sigma_o]*100$

Where: σ_1= The ultimate vertical pressure at any test.

σ_o= The ultimate vertical pressure at the initial condition without the presence of the top cemented sand layer.

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 (δ_i) to the maximum vertical settlement, without the presence of the top cemented sand layer (δ_o).

Table 1. Details of Experimental Testing Program.

b , cm	2.5			5			7.5		
H cm	40			40			40		
Hc/b	0.0	1.0	1.5	0.0	1.0	1.5	0.0	1.0	1.5
Hs/b	1.5	2.0	3.0	1.5	2.0	3.0	1.5	2.0	3.0
No. of test	9			9			9		

3.1 Effect of thickness of top cemented sand layer

Thickness of the top cemented sand layer (Artificially Cemented Sand) has a great effect on load-settlement relationship. The results obtained from these tests were calculated and plotted in the form of stress- settlement relationships as shown in figure 4. From this figure it can be clearly seen that the ultimate bearing capacity increases with the increase of thickness of cemented sand layer,(Hc/b) for any depth of underlying loose sand layer,(Hs/b) ratios. Also it decreases with the increase of the depth of the underlying loose sand layer,(Hs/b). The study of this figure elucidated that adding cement to top sand layer improves the behavior of the footing in the form of increasing the ultimate bearing capacity and reducing the settlement of the footing model. Typical Bearing Capacity Ratio-H/c ratio relationship is shown in figure 5. A rapid increase is seen in (BCR) with increase of the thickness of cemented top layer up to Hc/b =1.0 with further increase in Hc/b ratio the rate of improvement in the ultimate bearing pressure decreases. This indicates that there is an optimum value of Hc/b ratio at which maximum ultimate bearing pressure can be reached after which additional increase of thickness of cement becomes effectiveness. This may be due to the fact that below the footing their exists a zone of shearing deformation of soil and only that portion of reinforcement which lies within this zone will have its tensile strength effectively mobilized. An examination of the results shown on figure 5 elucidates that BCR will increase to at least 30% for footing of diameter =5.0 cm and Hs/b=1.5.

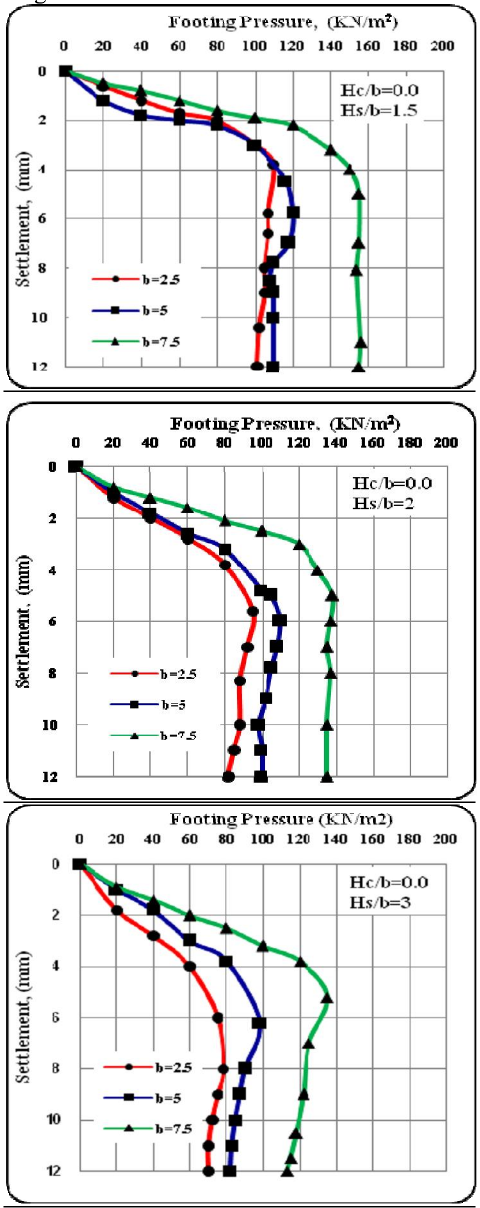

Figure3. Stress –settlement curves for various footing diameter on sand without cementation for different values of Hs/b ratio.

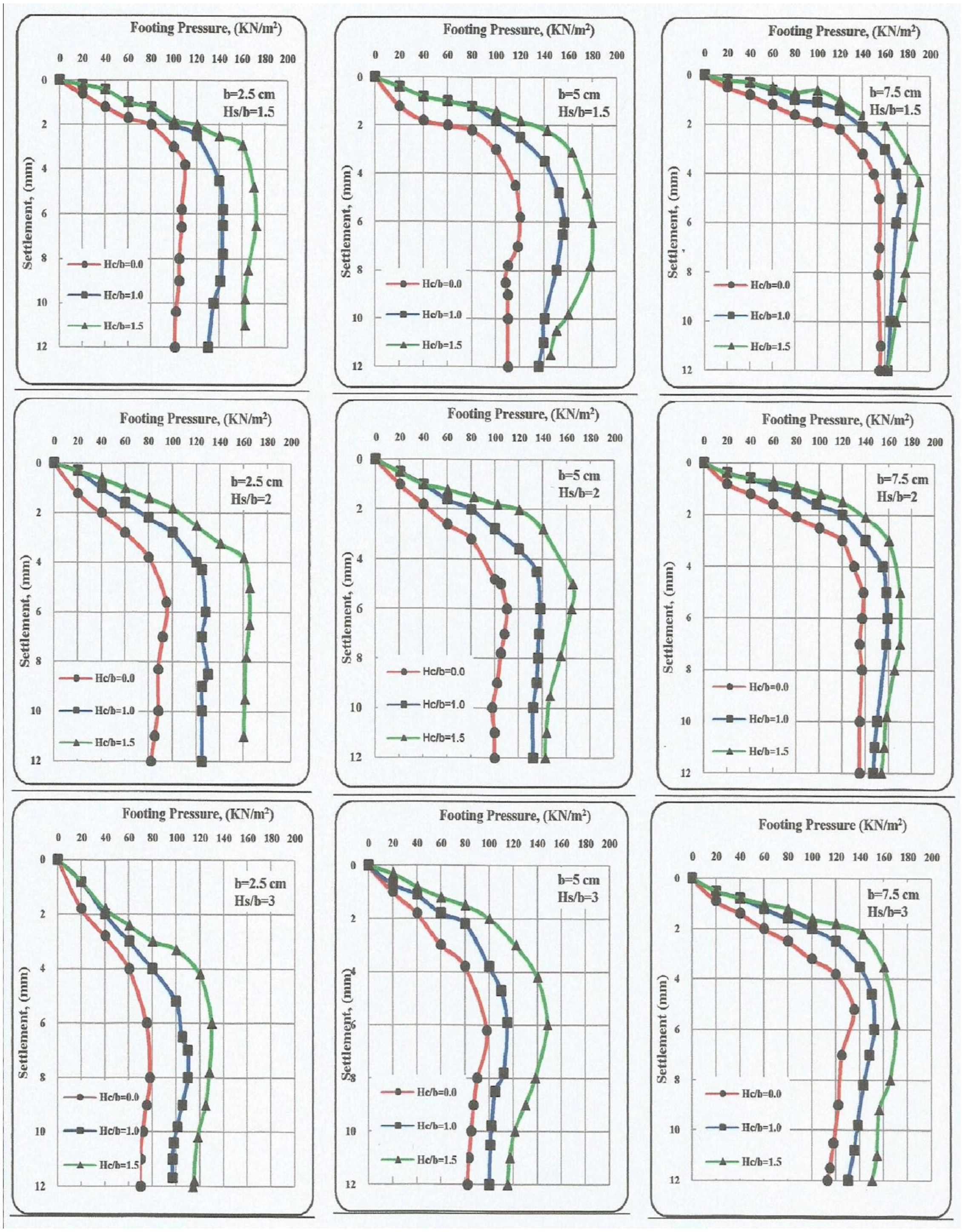

Figure 4. Stress-settlement curves for various footing diameter for different values of Hc/b ratio

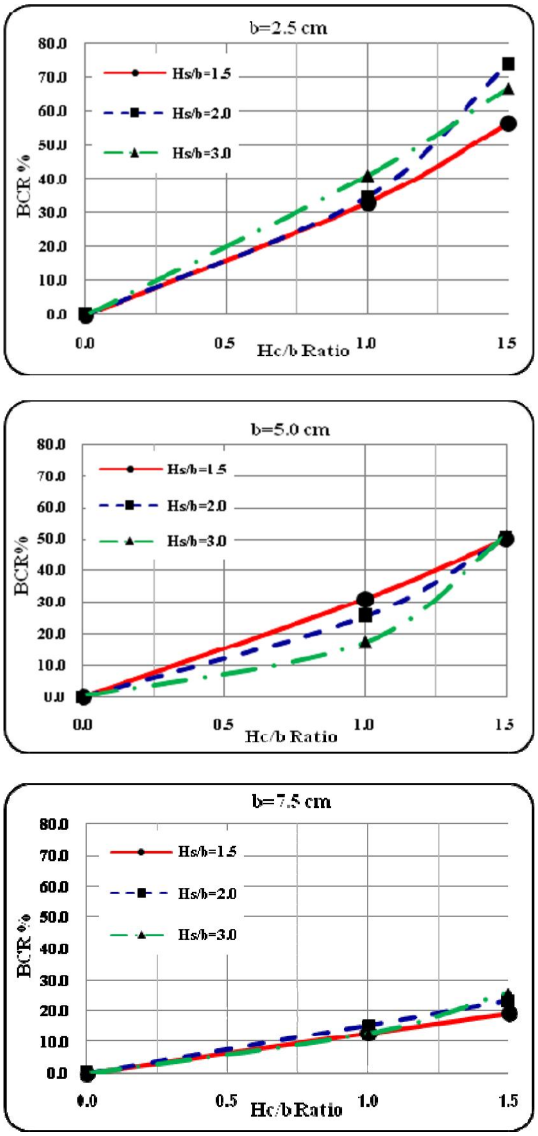

Figure5. Effect of thickness of top cemented sand layer on BCR.

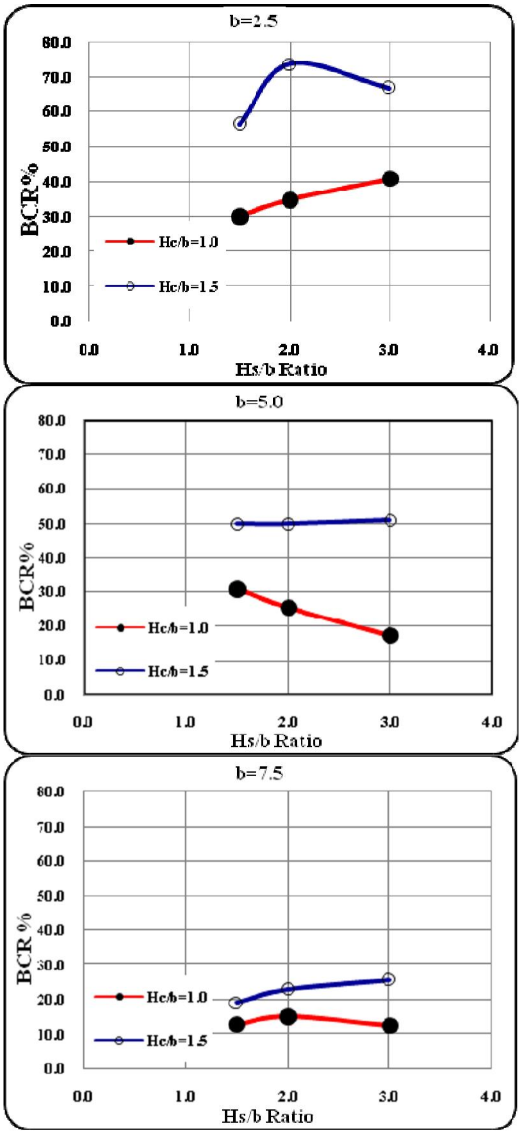

Figure 6. Effect of thickness of loose sand layer on ultimate bearing capacity.

3.2 Effect of thickness of loose sand layer

The thickness of loose sand layer below cemented layer has a great effect on load-settlement relationship. Figure 6 was plotted presenting the relation between thickness of loose sand layer, Hs/b ratio and Bearing Capacity Ratio (BCR%) for the studied Hc/b, ratios from this figure it is noticed that the presence of cemented layer increases the ultimate bearing capacity , and this increase is more obvious with the increase of cemented layer thickness, and the decrease of loose sand layer thickness. From studying the results shown on figure 6 it is evident that the suitable thickness of the upper cemented layer (replacement layer) whatever the thickness of the bottom loose sand layer is 1.5 times footing width. The meditation of the obtained results shown on this figure elucidated that increasing the thickness of loose sand layer below cemented layer reduces the increase in (BCR%). At Hc/b=1.5, the presence of weak loose sand layer has negligible effect on increase in ultimate bearing capacity. This output can be attributed to the fact that at great thickness of cemented top layer the failure wedge of the footing occur in this layer, which make the weak loose layer has no effect on the ultimate bearing capacity. Also it can be seen that increase in BCR% diminishes (nearly constant) at Hc/b equal to 1.5, but providing a rigid layer leads to change of the rate of settlement. The variation of (BCR) with Hs/b, ratio for various thickness of top cemented sand for various footing dimensions shown in figure 6 showed that (BCR) is observed to be maximum at Hs/b=2. in respect of all the studied Hc/b ratios. In the present study the results further indicate that the combination of Hc/b =1.5 and Hs/b=2.0 yield to maximum values of (BCR).

3.3 Effect of footing dimensions

The variation of ultimate bearing pressure with Hs/b, and Hc/b ratios for various footing dimensions is shown in figure 7. For all Hc/b and Hs/b ratios ultimate bearing pressure increases by increasing footing diameter. It can be seen from this figure that the degree of curvature of load-settlement curves decreased with the decrease of footing diameter.

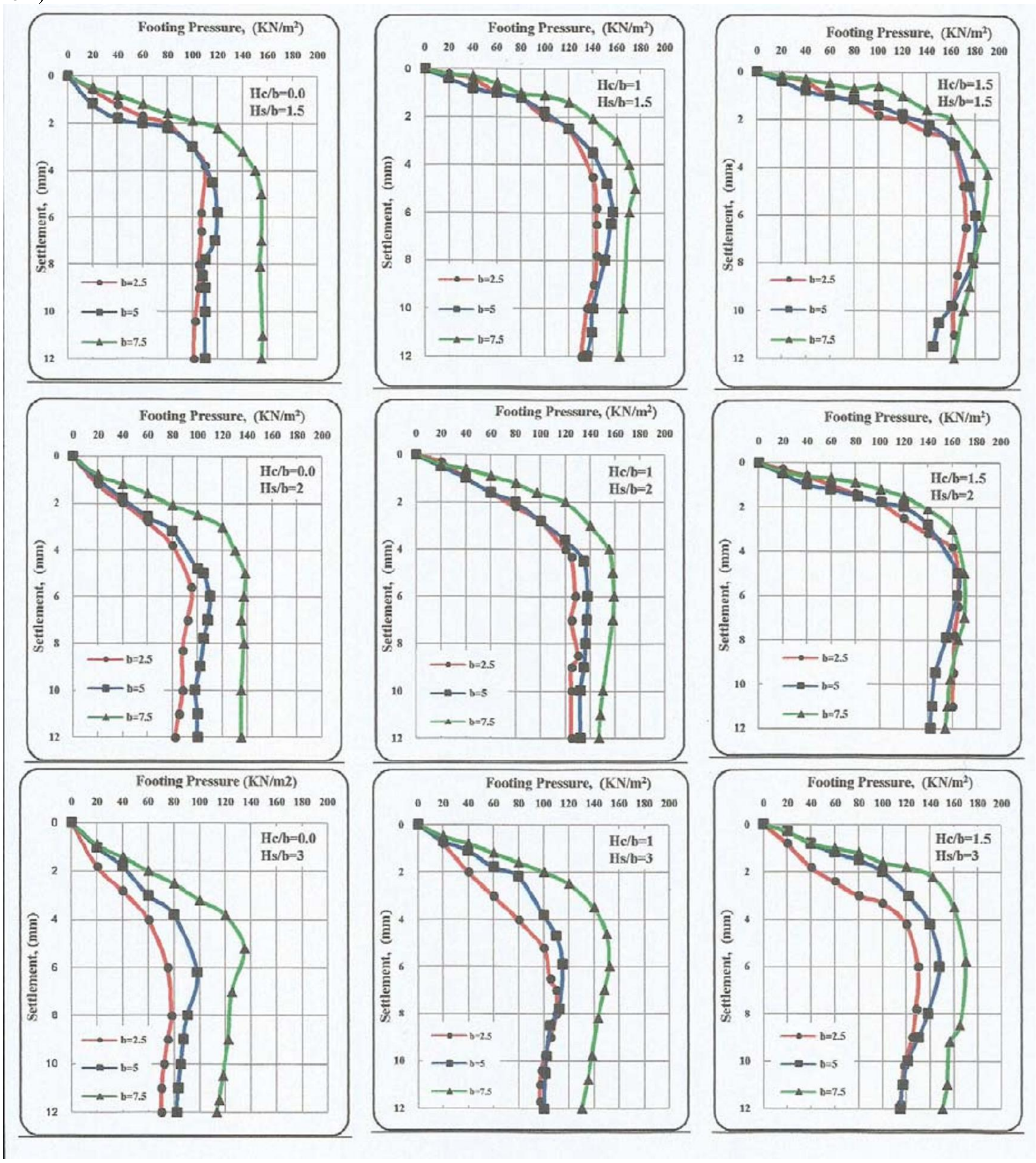

Figure 7. Stress –settlement curves for various footing diameter at different values of Hc/b and Hs/b ratios

3.4 Effect of depth of cementing upper sand layer on settlement.

The effect of depth of cementing upper sand layer on settlement was also studied (Figure 8). From the study of this figure it is seen that, by increasing Hc/b ratio,(SRF) decreases. Figure 9 was plotted presenting the relation between the thickness of bottom loose sand Hs/b and settlement reduction factor (SRF). It is noticed from studying this figure that the presence of cemented top sand layer decreases the settlement, and this decrease is more obvious with the decrease of thickness of bottom loose sand layer. To determine the suitable thickness of the upper cemented top layer that can fairly reduce settlement, figure 9 was studied, from this figure it can be concluded that the suitable height of cemented layer is equal to footing width.

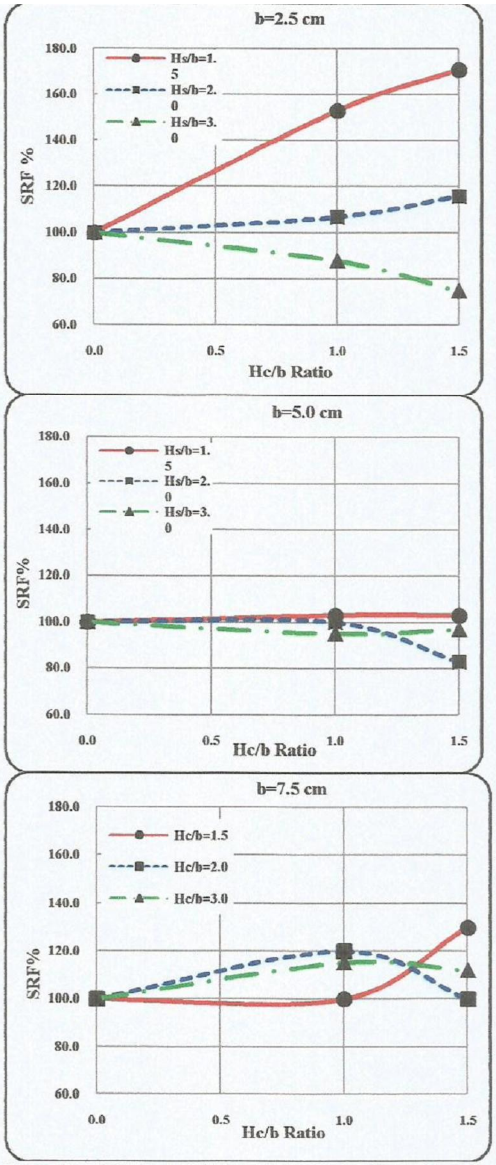

Figure8. Effect of thickness of top cemented sand layer on maximum vertical settlement

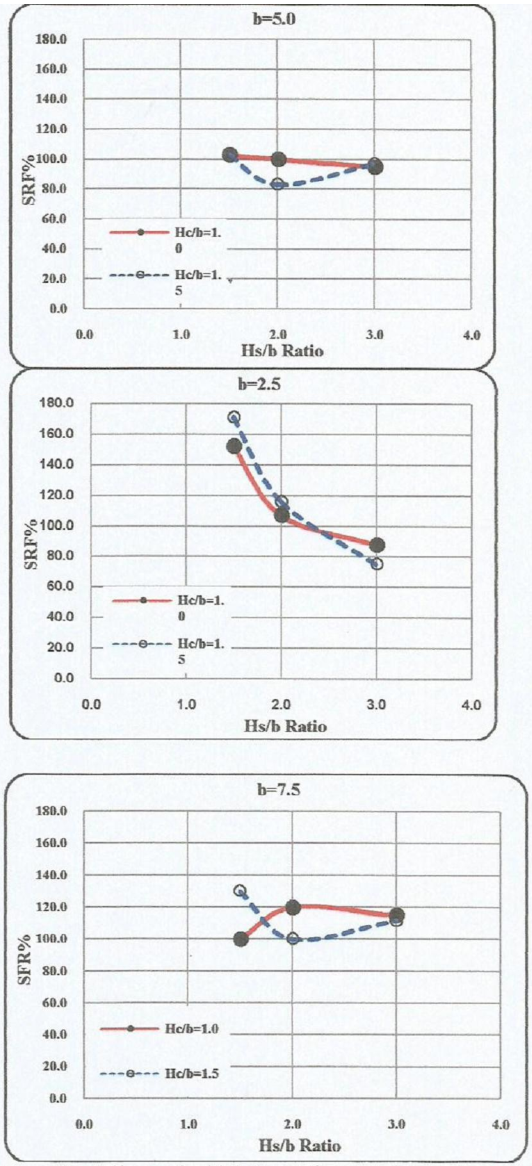

Figure9. Effect of thickness of sand layer on decrease in settlement.

4. Conclusions

The use of cemented sand layer instead of removing and re-compaction of sand replacement cushion above expansive soil was investigated experimentally using model circular footing. Based on the results presented and discussed in this investigation , the following conclusions can be drawn.

- Providing a cemented replacement layer on top of a relatively weaker soil layer reduces the settlement of footing founded on top of the replacement layer.
- The cemented top layer principally spreads loads, thereby reducing its intensity on the lower layer.
- Critical depth of cementing upper sand layer is 1.0 times footing width, after that increasing depth of cementation has small effect on increasing bearing capacity.
- Increasing the depth of top cemented sand layer to reach hc/b =1.5 make the presence of weak sand layer beneath it have no effect on ultimate bearing capacity whatever the thickness of the bottom loose sand layer.
- The combination of thickness of top cemented sand Hc/b =1.0 and depth of lower loose sand Hs/b=2.0 yield to maximum value of BCR.

Appendix 1: Notation

The following symbols are used in this paper

b : Footing diameter ; cm

H_C : Depth of cemented sand layer below foundation level; cm

H_S : Thickness of loose sand layer below foundation level; cm

H : Thickness of bottom stiff to very stiff clay layer; cm

q : Uniform surcharge ; KN/m^2

σ : Maximum vertical pressure; KN/m^2

BCR: Increase in maximum vertical pressure; %

δ : Maximum vertical settlement; mm

SRF: Decrease in maximum vertical settlement; %

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