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# Behavior of Different Footing Shapes on Sandy Layer Improved with Cement Underlain by Weak Clay Soil

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***Abstract*— One of the most important problems are to construct on soft clay soil. The utilization of a cemented top layer increases bearing capacity, reduces displacement at failure, and change soil behavior to a brittle behavior. The objective of this research paper is directed towards investigating experimentally the effect of footing shapes on the bearing capacity and settlement of weak clay soil overlain by cemented or uncemented sandy soil. Two percent of cement are used as reinforcement for sandy soils. A laboratory experimental work program was carried out on circular, rectangular, and square model footings. The studied parameters include footing shape, thickness of replacement sand layer, and percent of added cement. Experimental results show that the shape of the footing has a pronounced improving effect on soil bearing capacity and its settlement. Circular footing gives the highest improvement while rectangular footing gives the least one. The critical depth of cementing upper sand layer after which increasing depth of cementation has no effect on increasing bearing capacity was determined.**

**Keywords— soil bearing capacity, layered soil, weak clay, cemented sand replacement, soil reinforcement, footing shape.**

## I. Introduction

Soft clay deposits extended in Egypt in the north regions as a result of Nile sedimentation. Such soils 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. In such areas ground water table exists near the ground surface, which makes a problem when filling replacement layer. Also, good compaction of sandy replacement soil on its surface is practically impossible. These problems can be solved with the addition of cement to the used sandy soil. Investigations using model footing were done to evaluate the performance of using cement in reinforcement of top sand replacement. Several researchers such as (Meyerhof [11]; Burd and, Frydam [4]; Kenny and Andrawes [10]; and Hanna and Meyerhof [9]), study the behavior of shallow foundation on layered systems, concerning the case in which a sand layer overlies a soft clay layer. The studies of using sand reinforced with cement in layered soil has been studied by (e.g. Consoli et al. [5] and [6] ; and Shalaby S.I. 2[13] ).

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Vesic [1] classified the bearing capacity modes of failure into general, local and punching failure. If the soil is incompressible and has finite shear strength, a footing on this soil will fail in general shear, while if the soil is very compressible like soft clay it will fail in punching shear. The bearing capacity of shallow foundations besides the parameters and conditions of the soil below the formation depends on the shape of the foundation. The study presented herein describes the effect of varying percent of cement added to replacement sandy soil on the top of a weak clay deposit on the load-settlement behavior of footings with different shapes and have the same cross section area. The effect of percent of added cement, thickness of replacement layer and shape of footings on footing pressure-settlement relationships are investigated and evaluated.

## II. Bearing capacity solution for Sand overlying clay

The earliest attempt to calculate the bearing capacity of strong layer overlying a weak layer was that of Terzaghi and Peck. They assumed that the upper layer served principally to spread the footing load to a larger area on the lower layer surface. An analytical solution for layered cohesive-frictional soils, was proposed by Meyerhof and Hanna [8], which consider punching failure along straight lines following the foundation perimeter, might be effectively employed to predict the system ultimate bearing capacity. Meyerhof [7], studied dense sand overlying soft clay. The failure shape is a truncated pyramid pushed into clay. The friction angle ‘‘ϕ’’ and the soil cohesion ‘‘c’’ are both mobilized in the failure zone. Hanna and Meyerhof [2] developed a method, supported by model footing tests, which assume that the forces acting on vertical shear planes are the total passive earth pressure inclined upwards at an angle * to horizontal. Exact solutions introduced by Kenny and Andrawes [10] allow development of a simple method to solve this problem. Semi empirical approaches for calculating the bearing capacity of multi-layer soils have also been proposed based on experimental studies by Meyerhof and Hanna [8]. Hanna and Meyerhof [9] cover the case of footings on subsoil of dense sand overlying soft clay and presented the results in the form of design charts. Oda and Win [12] investigated the ultimate bearing capacity of footings on a sand layer overlaying a clay layer. They concluded that plastic flow occurs in the lateral direction in the clay layer, exerts drag force on the upper sand layer which results in loss of bearing capacity. AbdulhaHz O. et al. [3] calculated the bearing capacity of weak clay layer overlaid by a dense sand layer, based on the assumption that the pattern of the failure surface is a punching shear failure through the sand layer. Consoli et al.[5] investigated the utilization of a layered system made up of a top sand-cement layer overlaying a residual soil stratum using a plate loading test, soil behavior changes into a brittle behavior.

# III. Experimental work

## A. *Experimental Setup*

The experimental setup consists of a loading frame, a tank, a model footing, and the stress and settlement measuring devices. The container is a part of steel pipe of inner diameter of 76.2 cm, 1.27 cm thickness, and 73.75 cm height. A loading frame provided with a hydraulic jack was used in applying the load on the model footing. Three footing models made of steel with different shapes namely circular of diameter = 12 cm., square of dimensions 10.6×10.6 cm., and rectangular of dimensions 7.5×15 cm. which have the same surface area (112.5cm$^2$) and molded from steel plate of 2.5 cm thickness were used to simulate rigid footing condition. The magnitudes of the applied loads were recorded with the help of a sensitive pressure gauge and proving ring of 50 kN capacity. Two dial gauge with accuracy 0.01 mm and maximum travel 50 mm were used to measure the correct vertical settlement of the footings for each increment of the applied load.

## B. *Test Materials*

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

**Sand**: The sand used in this study was brought from El-Haram desert. Only the portions passing from 2mm -sieve and retained on 0.106 mm-sieve are used. The grain size distribution showed a uniformity coefficient equal to 2.5; curvature coefficient=1.15; mean grain size=0.55mm.This sand was classified as SP according to Unified Soil Classification System. The specific gravity of the particles was found to be 2.64. Laboratory tests on this sand indicated maximum and minimum void ratios of 0.692 and 0.443, corresponding, respectively. Direct shear tests were performed on air-dry samples at an initial relative density of 70%. The, same relative density achieved in the model tests. The mean angle of internal friction was found to be 34.6$^{\circ}$.

**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, and this type of clay was classified as clay with high plasticity (CH) according to unified soil classification system.

The clay was mixed during model tests at water content of 45% 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 17.0 KN/m$^3$ and 17.5 KN/m$^3$. with water content of 43.1 % and 40.3 %, respectively. The degree of saturation varied between 91% and 93%. 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/m$^2$.

The used sand in this study was thoroughly mixed with the chosen values of cement, 6% and 12% of dry sand by weight. Water was added to obtain an overall water content of 16% and 21% respectively, which corresponds the optimum moisture content based on the results of modified proctor compaction tests.

## C. *Experimental Procedure*

The model test shown in fig.1 was prepared by placing the lower clay layer in the testing mould in layers not more than 4.0 cm thickness to avoid the formation of air voids, 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 varies between 15 to 22 kN/m$^2$. The total thickness of the clay layer in the tank model is 40 cm. and this thickness was kept constant in all model tests. 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 sand cement mixture required to form the top cemented sandy layer was mixed with the required water to produce the optimum moisture content, and left for 5 minute after adding water 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. Equal increments of load were applied and maintained for at least 5 minute till all movements had ceased based on recorded deflection readings. Measurement of applied load and corresponding settlement was continued until the entire load settlement curve to failure was obtained. Based on the reading of the proving ring and dial gauge, stress-settlement curve were computed and plotted.

## D. *Testing program*

To study the effect of adding cement to the replacement sandy soil on the stress-settlement behavior of various footing shapes resting on weak clay layer, a series of laboratory model footing tests under axial loads were performed. The parameters studied are; footing shape, thickness of cemented sand layer Hc/b and % of added cement to sandy soil replacement.

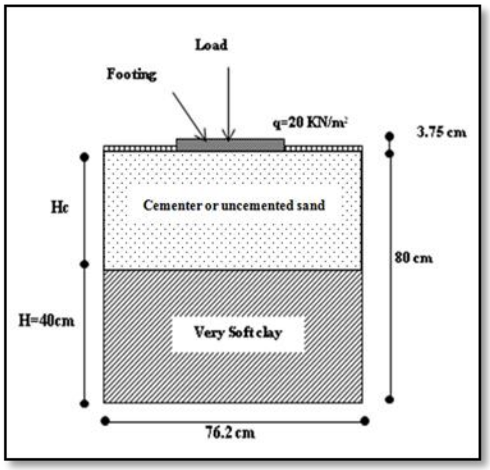


Figure 1. Experimental model setup

In all model tests the thickness of the cement-sand layer is represented in dimension less ratio Hc/b = 0.0, 0.5, 1.0, 1.5, 2.0 and 3.0 where (Hc) is the thickness of sand layer and (b) is the smallest dimension of the footing. All experimental work stops at Hc/b=3.0 for practical purposes. Table 1, presents the different parameters and the testing program. A total of 48 laboratory tests were performed.

# IV. Results and analysis

In this study, the ultimate bearing capacity in any test was defined as the load corresponding to the point of intersection between the initial, straight portion of the footing pressure-settlement curve and the steeper, straight portion of the end curve. An initial set of reference tests was performed for different footing shapes resting directly on soft clay bed without cemented or uncemented sand cushion as shown in Fig.2. The plotted relationships show that the footing pressure-settlement curves get flatter to x-axis in case of circular footing and square footing comparing with the case of rectangular footing .The footing pressure-settlement relationships for different footing shapes using top cemented or uncemented sand cushion are illustrated in Fig.3,Fig.4, and Fig.5. Hc/b is defined as the ratio of the sand replacement thickness (Hc) to the smallest dimension of footing (b). The load-settlement curves were found to reach a peak value at larger Hc/b ratio, where the mode of failure was general shear.

TABLE I. DETAILS OF LABORATORY TESTING PROGRAM

| Type of footing shape | % of added cement | | | Thick. of cemented sand layer (Hc/b) | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 0.0 | 6.0 | 12.0 | 0.0 | 0.5 | 1.0 | 1.5 | 2.0 | 3.0 |
| | Circular | | | | | | | | |
| | Square | | | | | | | | |
| | Rectangular | | | | | | | | |

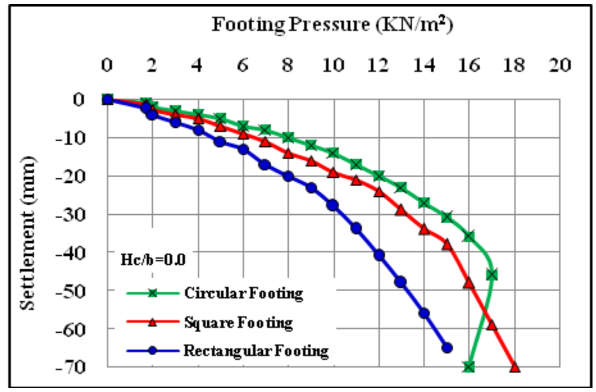


Figure 2. Load settlement curves for different footing shapes on soft clay.

The contributions of sand replacement layers on the bearing capacity are presented by the term Bearing Capacity Ratio (BCR). The following definition is used for (BCR):

$$BCR = q_r / q_o \qquad (1)$$

Where $q_r$ and $q_o$ are the bearing capacity for the (replacement cemented or uncemented sand layer placed on soft clay deposit) and (soft clay deposit) soils, respectively.

## A. *Effect of thickness of sand replacement layer*

Thickness of the top replacement sand layer has a great effect on load-settlement relationship. From these figures it can be clearly seen that the ultimate bearing capacity increases with the increase of thickness of cemented sand layer,(Hc/b). The results plotted in figure 6 show that for all the studied footing shapes, a rapid increase is seen in the ultimate bearing capacity with the increase of the thickness of cemented top layer up to Hc/b =2.0 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 cemented layer 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 cementation which lies within this zone will have its tensile strength effectively mobilized. At higher values of Hc/b the failure mechanism is characterized by punching shear failure in the top portion of replacement sandy soil and has no effect on bearing capacity in the lower part of replacement soil.

Fig. 7 shows the variation of Bearing Capacity Ratio, BCR with thickness of replacement top sand layer (Hc/b) for different percent of added cement for all the studied footing shapes. It has been found that the Bearing Capacity Ratio (BCR) is gradually increased with the increase of the replaced depth. A significant increase in the bearing capacity ratio is observed at (Hc/b > 1.5), the rate of increase in the Bearing Capacity Ratio after Hc/B = 2.0 decreases.

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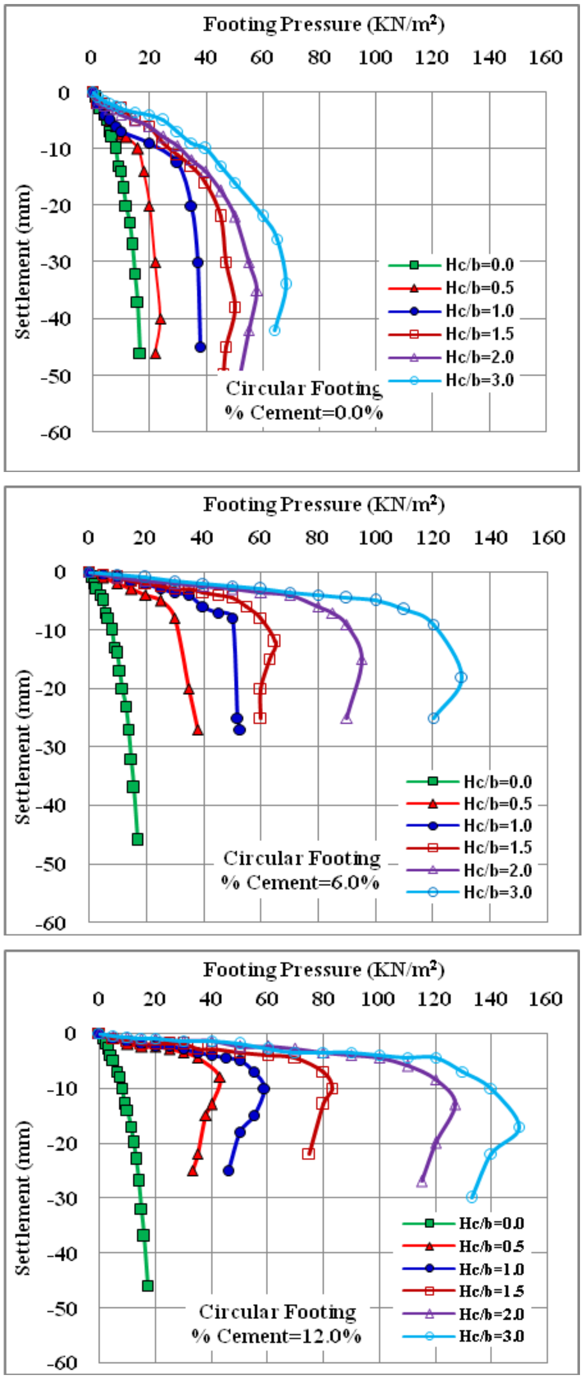



Figure 3. load settlement curves for circular footing on cemented, uncemented sand overlaying on soft clays for various Hc/b ratios.

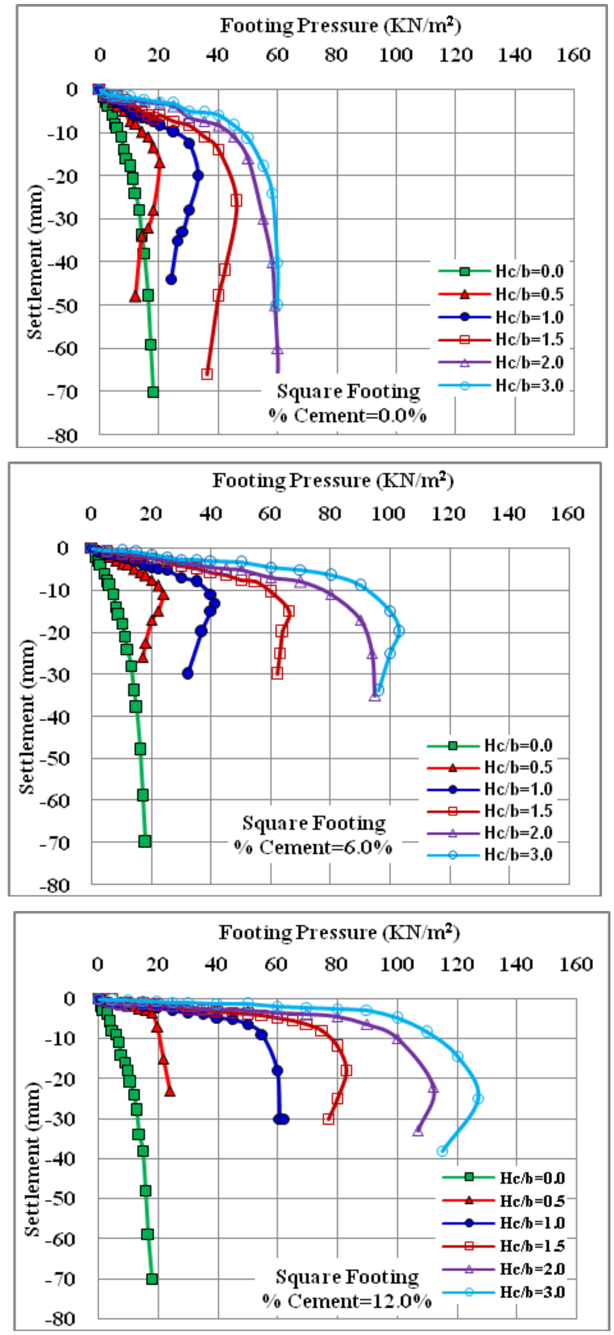



Figure 4. load settlement curves for square footing on cemented, uncemented sand overlaying on soft clays for various Hc/b ratios.

The degree of improvement on BCR mainly related to percent of added cement to replacement sand layer, wherever as the percent of added cement reaches 12% and the thickness of replaced soil, Hc/b = 3, the bearing capacity ratio increases by about 200%, this is valid for all the studied footing shapes.

## *B. Effect of percent of added cement to top sand layer*

The percent of cement added to top sandy replacement layer has a great effect on load-settlement relationship. Figure 8 was plotted presenting the relation between the percent of added cement and ultimate bearing capacity for the various studied footing shapes for all the tested thickness of sandy replacement layer (Hc/b). The study of this figure elucidated that adding cement to top sand layer improves the behavior of the studied footings. This increase in bearing capacity is more obvious with the increase of

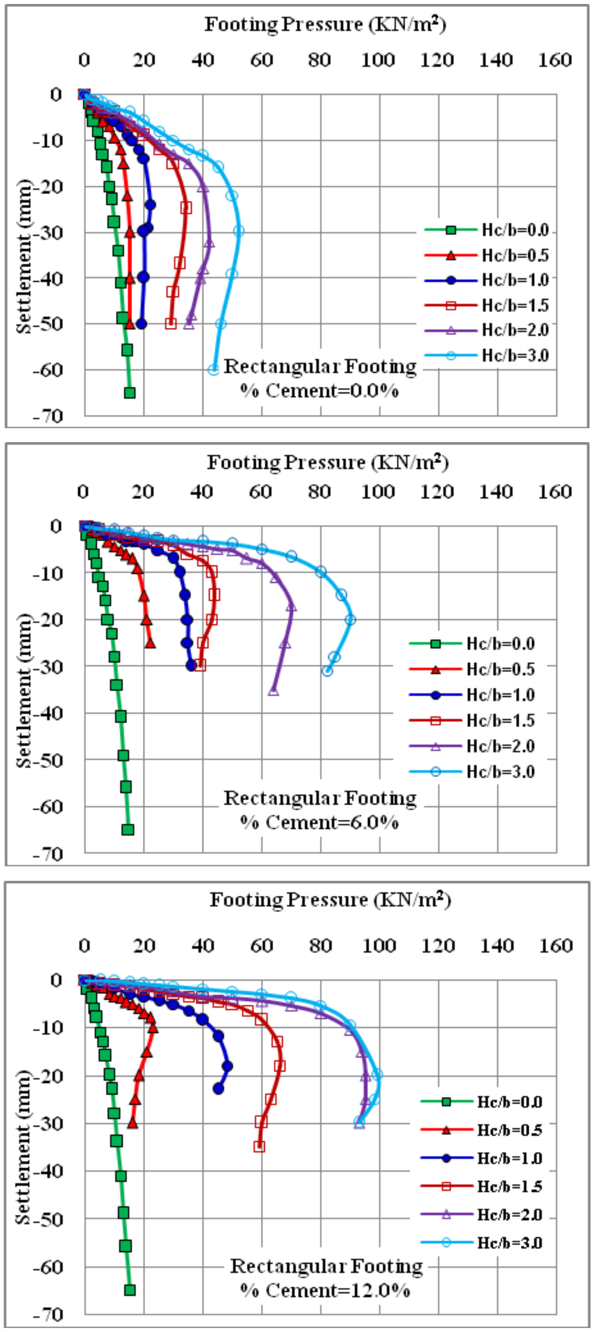



Figure 5. load settlement curves for rectangular footing on cemented, uncemented sand overlaying on soft clays for various Hc/b ratios.

sand layer thickness. From studying this figure it is evident that the suitable thickness of the upper cemented layer whatever the percent of the used cement is Hc/b=2.0. It is noticed that the percent of added cement to replacement top sand layer have a great effect in increasing the degree of improvement compared with case of footing on sand replacement without cementation. As can be seen from Fig. 8, mixing the sand replacement cushion with cement make the underneath weak layers sustain higher stresses, due to the new load distribution by the cementation.

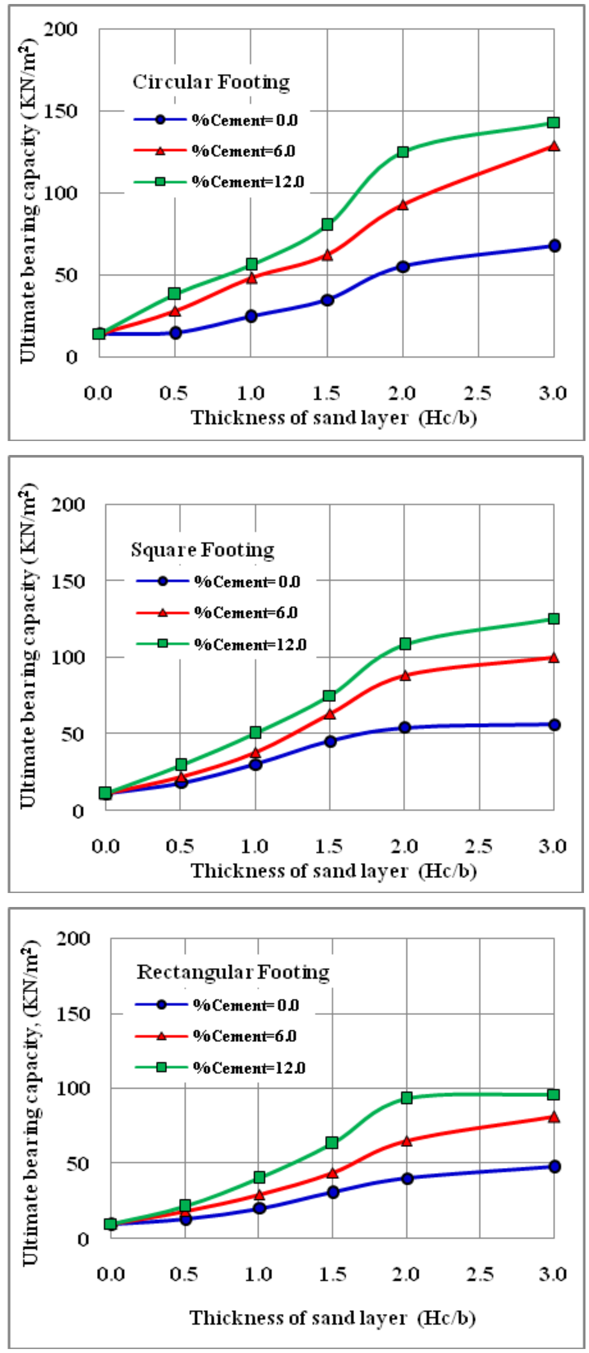



Figure 6. Varation of ultimate bearing capacity with thickness of sand layer Hc/b ratio.

By comparing the ultimate bearing capacity obtained from the use of 12% cement and that from the use of 6% cement for the tested footing shapes we find that the enhancement in bearing capacity due to the use of higher percent of cement (12%) can be achieved by increasing thickness of sand layer, Hc/b by one step, we say that the bearing capacities are the same. This means that, using 12% cement can increase the bearing capacity or reduce the thickness of sand cushion by about 50%. Using reinforced sand layer with cement, improved the ultimate bearing capacity for all shape footings.

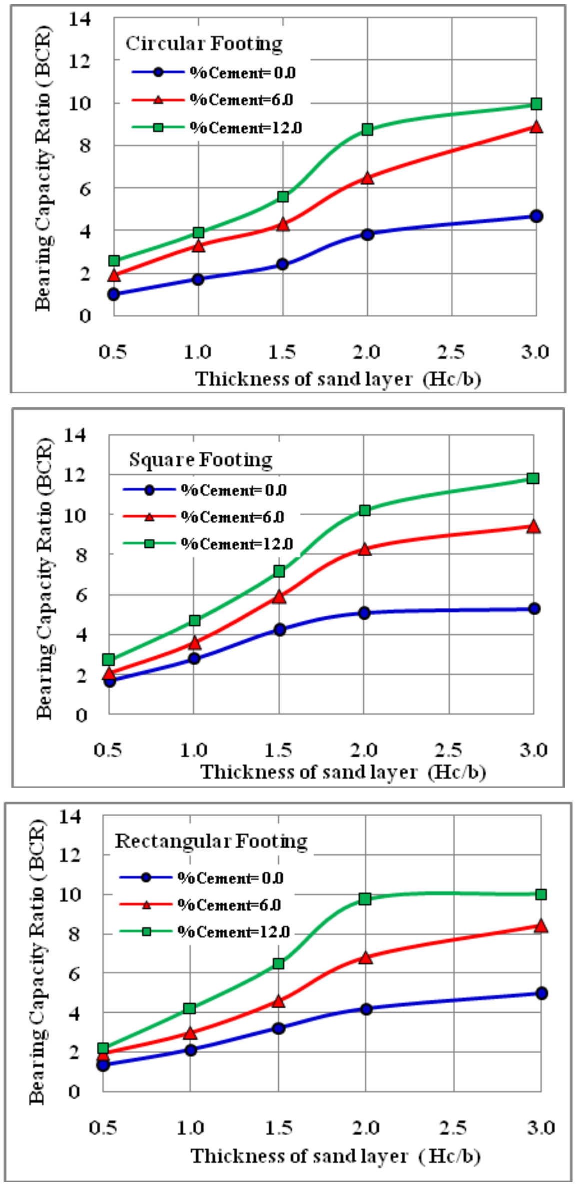
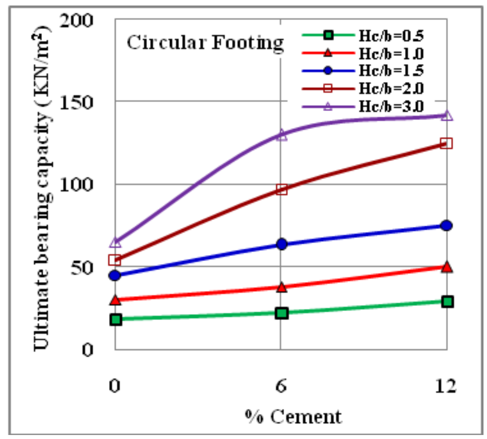


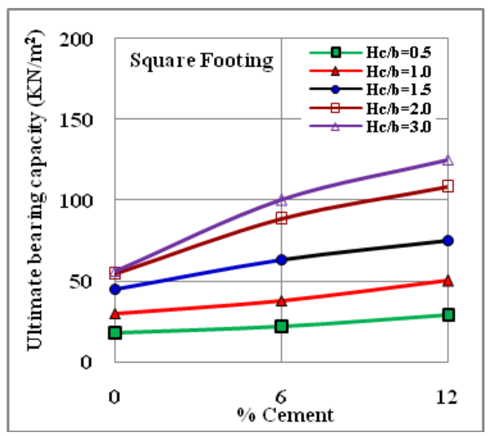

Figure 7. Varation of bearing capacity ratio, BCR with thickness of sand layer, Hc/b ratio.

This phenomenon can be explained as the addition of cement gave a better redistribution of the stress under the footing and this cause the stress reaching the clay surface is smaller than that when using uncemented sand layer.

## C. *Effect of footing shapes*

The variation of ultimate bearing pressure with Hc/b, and percent of added cement to sandy replacement layer for various footing shapes is shown in figure 3, 4, and 5. From the study of the plotted results, it is clear that the shape of footing has a great effect on ultimate bearing capacity and that the circular footing has the greatest value of ultimate bearing capacity comparing with other footing shapes. It can be seen from these figures that the relationship between the bearing capacity-settlement ratios for all the curves is fairly linear for small-load ranges, and that the relationship is nonlinear for large-load ranges and exhibit a peak values. The meditation of the obtained results shows that at the same bearing capacity for all studying tests, the circular footing gave the smallest value of settlement while the rectangular footing gave the greatest value.



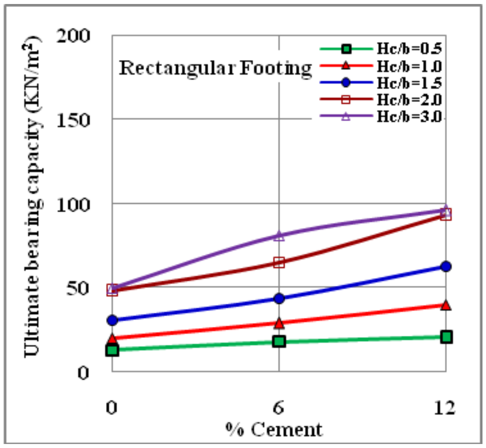



Figure 8. Effect of cement % on bearing capacity with tickness of sand layerk, Hc/b ratio.

## I. Conclusions

A series of laboratory model tests for the ultimate bearing capacity of a circular, square, and rectangular footings supported by a sand cushion underlain by weak clay with or without cementation of the sand cushion has been presented. Based on model test results, the following conclusions can be drawn.

1) Providing a cemented replacement layer on top of a relatively weaker soil layer increases the ultimate bearing capacity and reduces the settlement of footing founded on top of the replacement layer.

2) The cemented top layer principally spreads loads, thereby reducing its intensity on the lower weak layer.

3) Circular footing shows the highest value of ultimate bearing capacity comparing with other shape footings of the same cross section area resting on the same soil condition.

4) Critical depth of cementing upper sand layer is 2.0 times footing width, after that increasing depth of cementation has small effect on increasing bearing capacity and decreasing settlement.

5) Cementing the sand replacement cushion may offer cost saving by reducing the required thickness of the compacted sand cushion by up to 50%. (or alternatively increases the bearing capacity).

## II. Appendix 1: Notation

The following symbols are used in this paper
b : Smallest dimension of footing ; cm
Hc : Depth of replacement sand below foundation; cm
H : Thickness of bottom soft clay layer; cm
q : Uniform surcharge ; $KN/m^2$
$q_o$ : Bearing capacity of natural clay deposit; $KN/m^2$
$q_r$ : Bearing capacity for replacement layer; $KN/m^2$
BCR : Bearing capacity ratio

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About Author (s):

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