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The Behaviour of confined granular soil loaded by a square footing

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Abstract

This research involves the behaviour of confined granular soil supported by a square footing. A series of bearing capacity tests were carried out on a small-scale laboratory model, which filled with sand, placed in a dense state and confined with UPVC cell. The response of an unconfined state was measured in the beginning, and then compared with the confined sand. The studied variables included the cylinder height and diameter, the depth of the footing to the top of the cylinder and the embedded depth of the footing.

The test results indicated that the soil confinement resists lateral displacement of sand underneath the footing, which is leading to a significant improvement for the response of the footing. The curves of load-settlement generally showed the same trend in all the cases. Failure was considered as a settlement, which was equal to 8% of the total footing width. Also, the recommended optimum cell height, diameter, footing depth to the top of the cylinder and the embedded depth of footing that give the maximum bearing capacity improvement were presented and discussed. According to the present research results, a conclusion based on the soil confinement role and found to be notably increased the bearing capacity and stiffness. Furthermore, a modification of load–settlement behaviour of the sub grade sand was also gained.

List of Symbols:

b	Width of the square footing.
h	Height of UPVC cell.
d	Diameter of UPVC cell.
u	Depth of the footing to the top of the cell.
e	Embedded depth of the footing.
s	Settlement of the footing.
q	Bearing pressure
BCR	Bearing capacity ratio

Introduction

For weak soil conditions or heavy column loads, raft foundations are widely used for supporting structures. Then, for problems of a building adjacent to an old building, or a great foundation depth, braced excavation is required during foundation construction. An example for that, basement excavations, one of the available solutions is to use piles or sheet piles to support the excavation sides during construction. In other words, because of the difficulty of removing these piles, they became a part of the permanent structure and therefore two problems arise. The first one considers the structure analysis of the raft foundation (i.e. the piles are used as end support for the raft). The second one is the effect of these piles on the lateral movement of the soil underneath the raft foundation, in addition to the effect of this confinement on the bearing capacity of the soil. However, there are several solutions for the first problem such as isolating the raft from the piles; the confining effect of these piles on the raft behaviour is not clearly understood. As the problem is a smaller scale, it can be modelled as a square footing supported on a soil, which is surrounded by a confining cylinder. The strength of confined sand was studied by Ragagopal et al. [1]. They carried out a large number of triaxial compression tests to study the influence of geocell confinement on the strength and stiffness behaviour of granular soils. Several investigators have reported significant effects of soil confinement by using horizontal soil reinforcement to increase the bearing capacity of supported soils (Binquet and Lee [2], Fragaszy and Luwton [3], Guido et al. [4], Mahmood and Abdrabbo [5], Khing et al. [6], Mandal and Manjanath [7], Das et al. [8, 9] and Dash et al. [10, 11]...............etc.).

The aim of this research is to model and investigate the effect of soil confinement by piles on the behaviour of the soil foundation system.

2. MATERIALS AND METHODS

2.1: MATERIALS

2.1.1: The Soil

The soil used in the laboratory model tests of the current research was obtained from local areas at Kirkuk Governorate. To determine the grain size distribution of the soil sample, sieve analysis test was conducted according to the British Standards, BSI1377 [12]. It was found that the soil was granular poorly-graded sand and is SP according to the unified soil classification system. The soil has a uniformity coefficient $C_u = 3.267$, a concavity coefficient $C_c = 1.067$ with $D_{10} = 0.15$ mm, $D_{30} = 0.28$ mm and $D_{60} = 0.49$ mm as shown in Fig. (1).

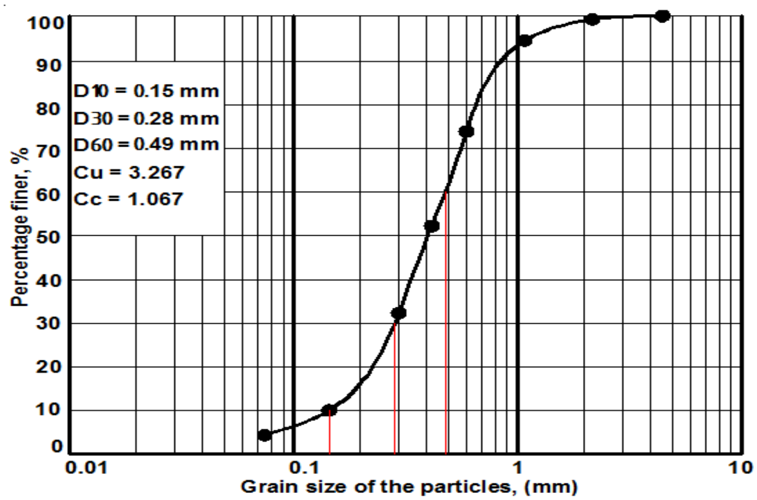

Fig. 1 Grain size distribution of the soil used in the laboratory model tests

The calculated soil particles specific gravity was 2.67 [12]. The maximum density of the soil was 17.98 KN/m^3 determined by means of compaction test [12], the minimum density was 15.32 KN/m^3 found by jar test method. The corresponding values of the minimum and maximum void ratios were 0.457 and 0.710 respectively. Sand raining technique was used to calibrate the sand density [13]. The sand was rained through a mesh of 2.87 x 2.87 mm opening using different heights of drop. Various values of placing density have given by the mentioned heights of drop [13]. Figure 2 shows the relation between drop height, density and relative density of the sand. It was decided to use dense state with density of 16.25 KN/m^3 throughout the investigation. This was obtained by 40 cm raining height, which yielded into a relative density of 67.25%. The soil grains' angle of internal friction was 35 degrees at the desired density, which was determined by direct shear test [12].

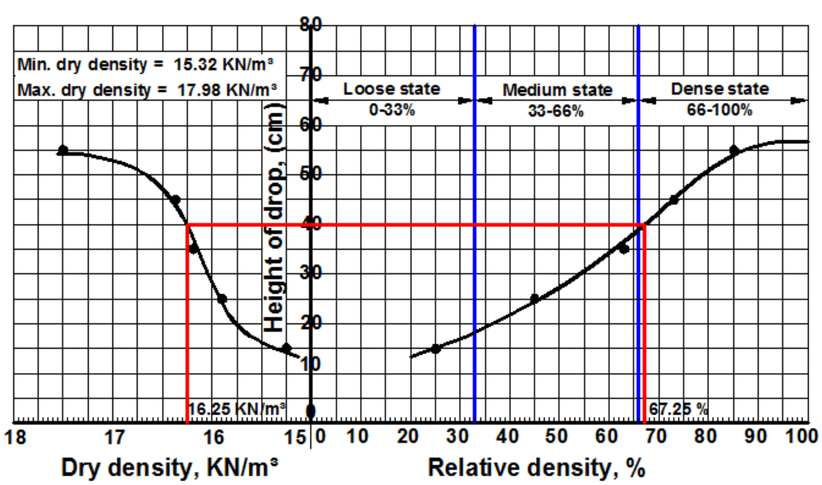

Fig. 2 Relation between drop height, density and relative density of the sand

used in the laboratory model tests (Calibration of the sand)

2.1.2: Confining cells

The confining cells were made of un-plasticized polyvinyl chloride UPVC cylinders with different diameters and heights. UPVC is produced from the polymerization of a vinyl chloride monomer with certain additives including heat stabilizers and lubricants. Its actual strength for any situation depends on the wall thickness uniformity, the rate of loading, and the temperature of plastic materials. The cylinders interior and exterior surfaces were made very smooth. The used diameters were 60, 120, 150, 180 and 240 mm, and the used heights were 100, 150, 200 and 250 mm. The thickness of the cylinder wall is 2.5 mm and its properties as given by the manufacturer are shown in following table 1. It was decided to carry out the entire test program with confining cylinders installed vertically after setting the sand deposits.

Table 1: Properties of the Un-plasticized Polyvinyl Chloride UPVC Cylinders, as given by the manufacturer

Test Type	***Value***
Maximum hydraulic pressure for 1 h at 23°C	*23 Bar*
Specific gravity	*1.42-1.43*
Shore hardness	*70-90 Degree*
Tensile strength	*500 Kg/cm²*
Bending strength	*950 Kg/cm²*
Modulus of elasticity	*3.2 x 10 Kg/cm²*
Impact strength	*4.7-5.4 Joules*
Water absorption	*1.05 Mg/cm²*
Elongation at break	*>80%*
Softening point	*80 °C*
Fabricating temperature	*110-140 °C*

3. METHODS

3.1: Testing apparatus

The overall view of the testing apparatus of this research is shown in figure 3.

The testing apparatus consists of:

1. A rigid steel frame 1.45 m height to support the box and prevent lateral displacement, which consists of four steel columns. These columns are firmly fixed in the four horizontal steel beams, which are firmly clamped in the lab ground using four pins.
2. A well stiffened wooden box of 560 x 560 x 500 mm as internal dimensions, with 25 mm side and base thickness. The base contains two 200 X 200 mm square holes, provided with control gates for emptying the box. The box front wall was 20 mm of thick glass.

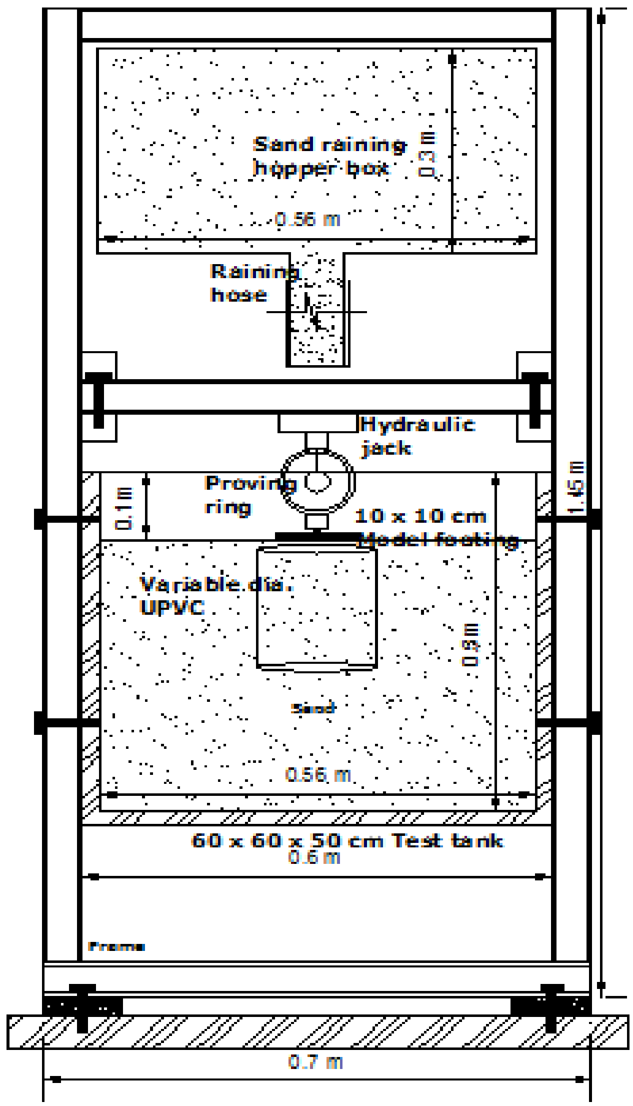

Fig. 3 Overall view of the testing apparatus of the research

3. The square footing model was 100 mm side length and 10 mm as a thickness, made of aluminium plate. The sand was glued to its base to simulate a rough base condition [1].
4. A recess was made into the plate to accommodate a ball bearing which was placed between the footing and the proving ring. Such an arrangement produced a hinge. The footing freely rotation was allowed by the hinge. At the approached failure, and potential moment transfer from the loading fixture was eliminated through which vertical load was applied to the footing uniformly.
5. Two dial gauges were placed on the footing in order to measure its settlement.
6. Sand raining hopper box (made of wood) was 560 x 560 mm in plan view and 300 mm in depth. The outlet of the hopper was connected to a flexible raining hose for easy control of the sand raining. The raining hose was of sliding type. It consists of two aluminium pipes, one sliding inside the other, thus providing good control of the raining height. To the end of the hose, a stainless steel mesh of 2.87 x 2.87 mm square opening was attached. This is to control the rate of flowing sand.

7. The loading system is mounted by a horizontal standard I section steel beam supported on the columns. It consists of a hand-operated 2 Tones capacity hydraulic jack and pre-calibrated load ring. Since the sand raining technique is used to deposit the sand inside the tank, the beam was designed to swing about one end. Therefore, the beam can be swung out during the deposition process of the sand from the sand raining box and returned back, when sand deposition is completed to the original loading position above the tank. The transferred load to the footing was conducted through the ball bearing.

3.2: Testing program

The main variables concerned in this research were:

a. Effect of cell diameter (d).
b. Effect of cell height (h).
c. Effect of footing depth to the top of the cell (u).
d. Effect of embedded depth of the footing (e).

The program of testing is divided into two groups as illustrated in the following points:

1. Group I: Only one test was done on non-confined sand.
2. Group II: Sixty three tests were done on confined sand, as follows:

a. Twenty tests to show the effect of the cell height (h = 10, 15, 20 and 25 cm) using footing depth to the top of the cell (u = 0 cm) for different cell diameters (d = 6, 12, 15, 18 and 24 cm).
b. Twenty tests to show the effect of the cell height (h = 10, 15, 20 and 25 cm) using footing depth to the top of the cell (u = 2.5 cm) for different cell diameters (d = 6, 12, 15, 18 and 24 cm).
c. Twenty tests to show the effect of the cell height (h = 10, 15, 20 and 25 cm) using footing depth to the top of the cell (u = 10.0 cm) for different cell diameters (d = 6, 12, 15, 18 and 24 cm).
d. Three tests to show the effect of embedded depth of the footing (e = 2.5, 7 and 10 cm) using cell diameter (d = 15 cm) and cell height (h = 20 cm).

While the other parameters such as width of the footing (b), relative density of the sand and cells type were kept constant.

3.3: Testing procedure

For both confined and unconfined sand tests, sand raining technique was used for the sand compaction via opening the raining hose lock. The control of the height of falling was conducted by sliding the hose up and down. Then, a constant height of 40 cm above the sand surface was kept. This was easily done along the outer part of the hose with the aid of guide marker. In order to obtain a dense state of backfill, this height was chosen after the collected information from the preliminary tests. A continuous movement of the raining hose was carried out, which moved forward and backward and in transverse directions. By using marking lines on the interior sides of the box as a guide, the layers of equal thickness of sand were placed in. At the time of the depth of the sand in the box approaches the design place, and for confined cases, the cell was pushed vertically into the sand, and then the model footing was centrally placed on the top of the confined sand deposit. Then, the two dial gauges were placed on the opposite sides of the footing to measure its settlement. After that, the load was applied on it by the hydraulic jack. The load was applied in small increments until reaching failure. Each increase in the load was constantly maintained, which lasted until the footing settlement had stabilized. Failure was defined as settlement equal to 8% of the footing width. The vertical movement's results were recorded; therefore the entire load settlement curve at failure was obtained. At the end of the experiment, and in order to discharge the sand from the box into a collection container, the locks of the base holes control gates were opened. In order to reuse the sand in the next tests, the collected sand was transferred to the hopper box.

4. RESULTS AND DISCUSSION

Because of the soil confinement, the improvement of the bearing capacity is represented by the bearing capacity ratio BCR, which is the ratio of the footing ultimate load with soil confinement (P) to the footing ultimate load without soil confinement (P_0). The footing settlement (s) is expressed in terms of the footing side width b as the ratio s/b%. The theoretical ultimate bearing capacity of a square footing can be calculated from Terzaghi's equation:

$$q_u = 0.4\ \gamma\ b\ N\gamma \quad ....(1)$$

Where:

γ : unit weight of the soil

b : width of footing

$N\gamma$: Terzaghi bearing capacity factor, which depends on the soil friction angle (φ).

The theoretical bearing capacity is 27.56 KPa. The measured ultimate pressure is 26 KPa, which shows close agreement to the theoretical value, and the associated ultimate displacement for the unconfined case is 4 mm.

Following table 2 shows the results of the ultimate pressure P and associated displacement s for the footing depth to the top of the cell u = 0, 2.5 and 10 cm and different cell diameter d and height h. Typical variations of bearing pressure with footing settlement ratios s/d with and without soil confinement for different heights of confining cells are presented in figure 4. It can be seen that both of the bearing capacity of the footing and the stiffness of the foundation bed were improved due to the installation of confining cylinders. It is apparent from the curves that the mode of failure is a general shear failure in which a pronounced peak can be observed in the load–settlement curve, after which the footing collapses and the load decreases [14]. Also, the value of the settlement ratio s/d at the ultimate load in the confined tests varied from about 7% to 10%. The observed improvement in the bearing capacity loads due to soil confinement along with the increase in the settlement ratio was reported by many investigators [15, 16].

From figure 4, it can be seen that the soil confinement process is improved the bearing load from 260 KPa for the unconfined case to 234 KPa for the confined soil using cells with d/b ratio of 1.50 and h/b ratio of 2.5 at the settlement ratio of about 8%. Therefore, it can be highlighted for cases when the excessive settlement is the controlling factor in determining the allowable bearing capacity, using confining cells may significantly decrease the settlement ratio for the same level of bearing load.

Table 2: Results of the ultimate pressure P and associated displacements s, for footing depth to the top of the cell u = 0, 2.5 and 10.0 cm, cell diameter d = 6, 12, 15, 18 and 24 cm, and cell height h = 10, 15, 20 and 25 cm

h (cm)	***d (cm)***	***For u=0 cm***		***For u=2.5 cm***		***For u=10.0 cm***	
		Ultimate pressure P (KPa)	***Associated displacements (mm)***	***Ultimate pressure P (KPa)***	***Associated displacements (mm)***	***Ultimate pressure P (KPa)***	***Associated displacements (mm)***
10	*6*	*48*	*0.93*	*42*	*1.87*	*27*	*3.73*
	12	*84*	*0.83*	*84*	*1.66*	*28*	*3.31*
	15	*104*	*0.78*	*88*	*1.56*	*29*	*3.11*
	18	*70*	*0.74*	*70*	*1.48*	*30*	*2.95*
	24	*56*	*0.69*	*56*	*1.37*	*31*	*2.74*
15	*6*	*60*	*0.84*	*52*	*1.67*	*32*	*3.34*
	12	*96*	*0.80*	*102*	*1.60*	*36*	*3.19*
	15	*122*	*0.75*	*112*	*1.50*	*40*	*3.00*
	18	*84*	*0.71*	*88*	*1.43*	*30*	*2.85*
	24	*70*	*0.65*	*70*	*1.31*	*34*	*2.61*
20	*6*	*76*	*0.78*	*66*	*1.56*	*37*	*3.11*
	12	*134*	*0.71*	*126*	*1.43*	*44*	*2.85*
	15	*156*	*0.59*	*140*	*1.17*	*51*	*2.34*

	18	*110*	*0.53*	*110*	*1.07*	*37*	*2.13*
	24	*86*	*0.61*	*86*	*1.22*	*28*	*2.43*
25	*6*	*104*	*0.69*	*92*	*1.38*	*28*	*2.75*
	12	*186*	*0.58*	*164*	*1.16*	*54*	*2.32*
	15	*234*	*0.52*	*190*	*1.05*	*61*	*2.09*
	18	*162*	*0.43*	*154*	*0.87*	*45*	*1.73*
	24	*122*	*0.30*	*118*	*0.61*	*40*	*1.21*

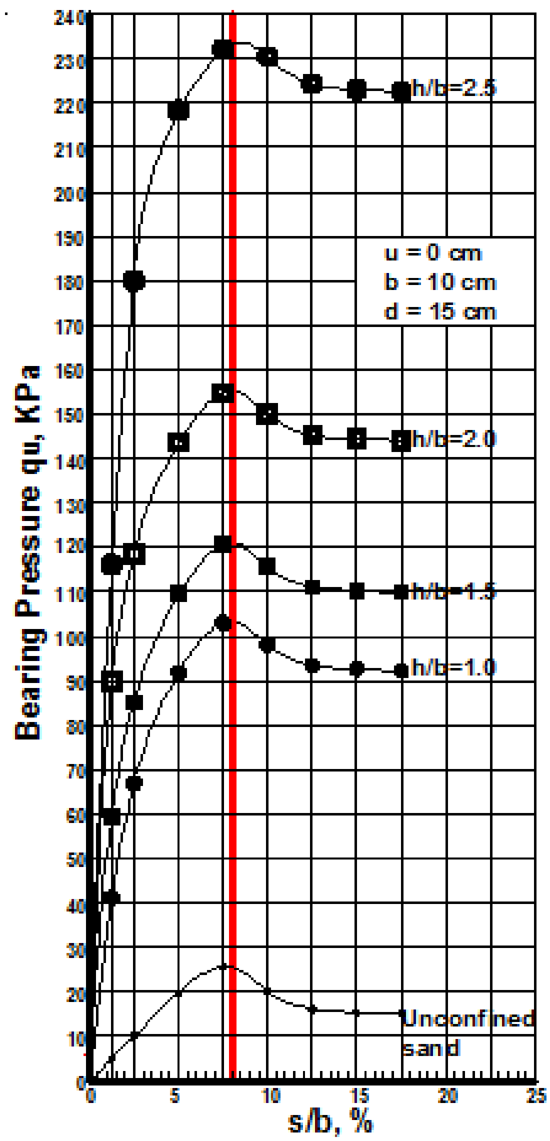

Fig. 4: Variation of bearing pressure with s/b ratio for different cell heights

Overview:

The following show the effect of the main variables concerned in this research:

A: Effect of cell diameter (d):

In order to determine the influence of cell diameter on the behaviour of the footing, five cells with diameters of 60, 120, 150, 180, and 240 mm were used. Figure 5 shows the variation of BCR with normalized cell diameter for different cell heights with a constant footing width of 100 mm. A significant increase in the bearing capacity of the model footing supported on confined sand with the increase of normalized cell diameter d/b is observed until a specific value, after that the BCR decreases with an increase in the d/b ratio. It was observed that as failure approached in tests carried out with small cell diameters, sand inside the cell and the cell behaved as one unit when the load was increased, the cell, sand, and the footing settled altogether. In tests carried out with large cell diameters, the mentioned behaviour was noticed initially. While, as the load was increased, it was no longer observed the footing settled down, but the cell was unaffected with the increase of the load.

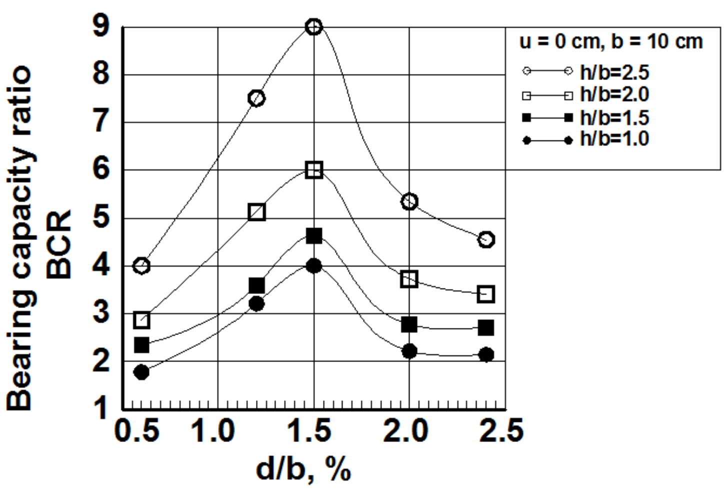

Fig. 5: Variation of bearing capacity ratio with normalized cell diameter

d/b for different cell height h/b

Figure 5 also shows that using soil confinement could result in an improvement of bearing capacity as large as 9 times and more than that without soil confinement. It is clear that the best benefit of soil confinement could be obtained with a d/b ratio between 1.2 and 1.8 with the maximum improvement of the bearing capacity at a ratio of about 1.5 for different heights of confining cells. This significant increase in the magnitude of the footing bearing capacity can be explained with the aid of figure 6 as follows. When the footing loaded, the confinement state provided two jobs: resists the lateral displacements of the soil particles underneath the footing, and confines the soil leading to a significant decrease in the vertical settlement.

Hence, the bearing capacity was improved. For small cell diameters, as the pressure is increased, around the edges of the footing the plastic state is initially developed, then spreads downward and outward.

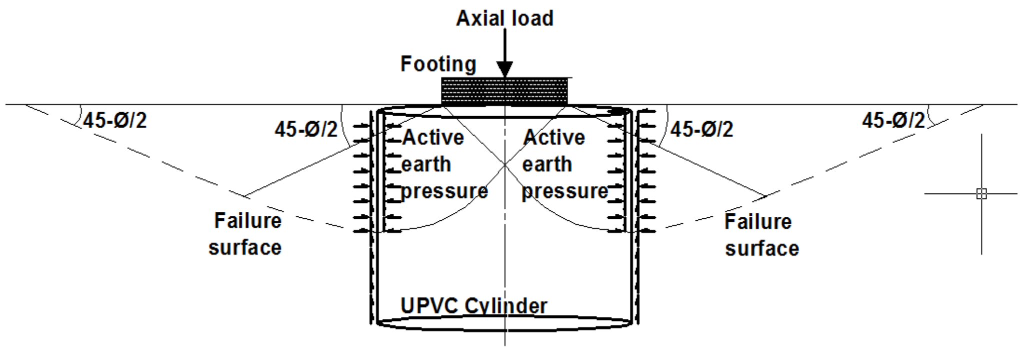

Fig. 6: Intersection of standard failure surfaces with the confining cylinder

The vertical frictions were mobilized between the sand and the inside wall of the cylinder increase with the increase of the acting active earth pressure until the point, when the system of the cylinder-sand-footing starts to behave as one unit. The behaviour is similar to that noticed state of deep foundations piles and caissons, in which due to the shear resistance of cell surface the bearing load increases. This illustrates the bearing load increase with the increase of both of the cell diameter and cell height. Based on the performed tests with cells made with very smooth surfaces, it can be concluded that increased surface roughness results in greater bearing load improvement.

In comparison to this response, tests carried out by Dash et al. [15, 16] on sand beds at a relative density of 70% and reinforced with geo-cell mattress, mobilized bearing capacity pressure as large as eight times the ultimate capacity of the non-reinforced sand. Also, tests carried out by Omar et al. [15, 16] and Khing et al. [6] on sand beds at a relative density of 75% and reinforced with planar reinforcement, failed with clearly pronounced peak loads of about five times the ultimate capacity of un-reinforced soil at settlements equal to about 20% of the footing width.

B: Effect of cell height (h):

In order to investigate the effect of cell height on the footing response, tests were carried out using four different heights for each cell diameter. The variation of BCR with normalized cell height h/b is shown in figure 7 for different normalized cell diameters d/b. This figure shows the same pattern of behaviour for the different cell diameters. Increasing cell heights results in a greater improvement in the BCR, which results in the enlargement of the surface area of the cell-model footing and leading to a higher bearing capacity load. The slope of the BCR versus h/b curves for d/b ratios of 0.6, 1.8 and 2.4 are less than the comparable slopes for d/b ratios of 1.2 and 1.5. This trend confirms the previous conclusion that the greatest benefit of cell confinement can be obtained at a d/b ratio of about 1.5.

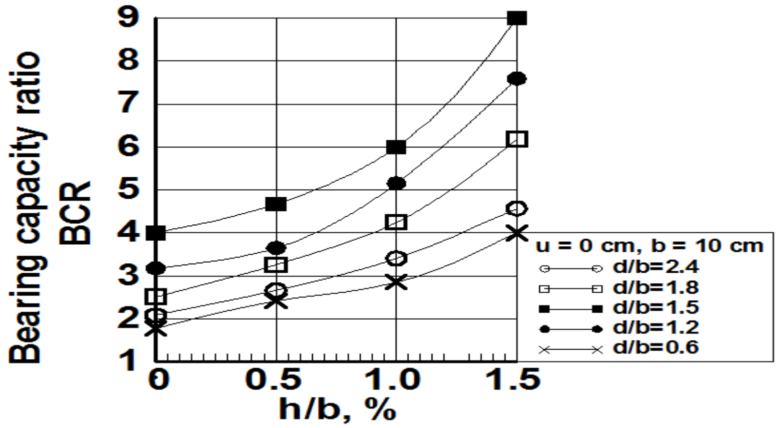

Fig. 7: Variation of bearing capacity ratio with normalized cell height h/b for different cell diameters d/b

C: Effect of footing depth to the top of the cell (u):

Figure 8 shows the variation of the BCR at different depths, which normalized to the top of the cell u/b for cells with d/b ratio of 1.5 and h/b ratio of 2.0. It is interesting to note that increasing the depth of the cell leads to an additional improvement in the magnitude of the bearing capacity until a specific value of u/b about 0.10 beyond which the BCR decreases with the increase in the depth of the cell. The initial increase in the BCR with u/b can be explained with the fact that the footing pressure spreads with increasing the depth acting over a larger area of the sand–cell system. With a further increase in the depth of placement, the soil between the footing and the cell top deforms laterally and, therefore, the vertical settlements increase and the BCR decrease as shown in table 2. Based on these results, it is recommended that the top of the cell should be at a depth of 0.1b from the bottom of the footing to get the maximum benefit. A similar recommendation was given by Dash et al. [10] when using geo-cell mattress to confine sand underneath a footing.

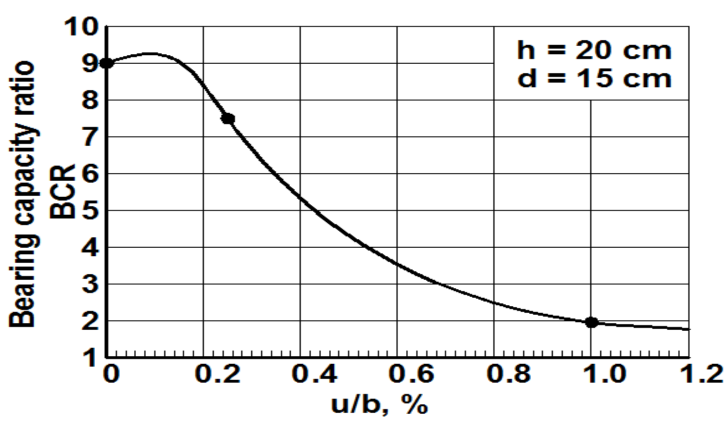

Fig. 8: Variation of bearing capacity ratio with normalized depth to the top of the cell u/b

D: Effect of the embedded depth of the footing (e):

In order to understand the effect of confining piles constructed to support soil cuts on the behaviour when the foundation level is low, a series of tests were carried out with all parameters held constant except the depth of the footing relative to the top of the cell. To accurately model the site condition, three conditions were evaluated. Cells with diameter equal to 15 cm and normalized depth of the footing to the cell height e/h values varied between 0.125 and 0.50 were used. Figure 9 shows the variation of BCR with normalized embedded depth e/h for cells with d/b of 1.5 and h/b of 2. It is clear that varying the foundation depth relative to the cell top has no effect on the behaviour of cell–model footing. The difference between the maximum BCR and the minimum value is 0.35, which is likely caused by the slight disturbance that occurs in the sand beds when placing the footing within the cell. This can be illustrated as follows. For unconfined footings, increasing the footing depth results in increasing the overburden pressure, hence increasing the bearing capacity. However, the influence of the overburden pressure is not recognizable for the confined footing. The footing settles and the plastic state are developed until the point at which the system starts to behave as one unit when the footing is loaded. Therefore, increasing the embedded depth affects only the initial part of the behaviour until that point after which the ultimate load depends on the surface area of the cell, which is constant. Hence, it can be highlighted that the embedded depth of a footing in confined granular soil has no influence on the footing–cell system response.

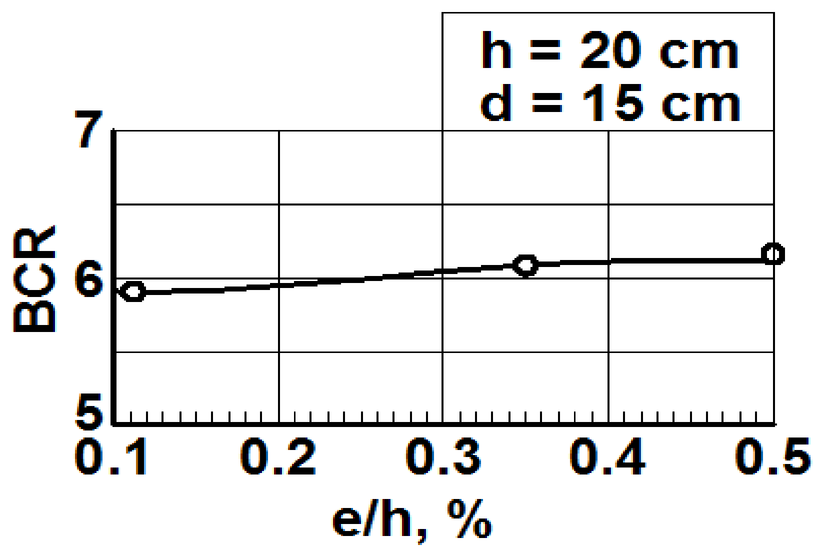

Fig. 9: Variation of bearing capacity ratio with normalized embedded depth e/h

5. CONCLUSION & RECOMMENDATION

Based on the experimental test results, the following conclusions can be drawn:

1. Soil confinement has a significant effect to improve the behaviour of granular soil subjected by a square footing. The ultimate capacity was found to increase by a factor of 9 as compared to the non-reinforced case.
2. Cells with different heights, diameters, and thicknesses could be placed beneath the individual footings leading to a significant improvement in their response.
3. Soil confinement can be used to obtain the same allowable bearing capacity at a much lower settlement in cases where structures are very sensitive to settlement.
4. For cases with small d/b ratio, the cell–sand–footing system behaves as a deep foundation, settles all together and the failure occurs as a shear failure in the soil surrounding the cell.
5. For cases with large d/b ratio, the cell–sand–footing system behaves initially as deep foundation, as the failure approaches, only the footing settles while the cell seems to be unaffected.
6. The BCR is highly dependent on the d/b ratio. The optimum value is about 1.50 which is regarded as cross point below and beyond which the improvement decreases.
7. Increasing the surface area of the cell–model footing caused by increasing the height of the confining cell, this transfers footing loads to deeper depths and leads to improve the BCR.
8. To obtain maximum improvement, the top of the confining cell should be situated at a depth of 10% of footing width from the bottom of the footing.
9. The embedded depth of the footing relative to the top of confining cell seems to have a negligible effect on the response of footing–cell systems for small diameters $d/b < 1.2$.

This paper object is to examine the effect of soil confinement on the behaviour of shallow foundations. Only the case of square footing supported on dry sand and surrounded from all sides is modelled using confining cells with very smooth surfaces. The behaviour of other footings circular or rectangular along with the influence of the roughness and the stiffness of cell material were not studied. Therefore, it is recommended that future work investigates the effect of these parameters for both dry and wet sand conditions. Studying the effect of soil confinement on the behaviour of footings bearing on weak types of soils, such as loose sand and soft clay, is intended by the writer.

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