



EFFECT OF REINFORCEMENT DENSITY ON THE BEHAVIOUR OF REINFORCED SAND UNDER A SQUARE FOOTING

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ABSTRACT

In this study, the behaviour of reinforced sand under a square footing has been investigated. A series of bearing capacity tests were performed on a small-scale laboratory model, filled with a poorly-graded homogenous bed of sand, which was placed in a medium dense state using sand raining technique. The sand was reinforced with 40 mm wide household Aluminium foil strips. The aim was to study the load-settlement behaviour, bearing capacity ratio and settlement reduction factor, considering the effect of reinforcing strip length, with various linear density of reinforcement, number of reinforcement layers and depth of top layer of reinforcement below the footing.

Generally the relation of load-settlement showed similar trend in all the tests. The failure was defined as the settlement equal to 10% of the footing width. The recommended optimum reinforcing strip length, linear density of reinforcement, number of reinforcement layers and depth of top layer of reinforcing strips, that give the maximum bearing capacity improvement and minimum settlement reduction factor were presented and discussed. Both bearing capacity and settlement reduction factor versus length of the reinforcing strips relation at failure have showed an improvement of the bearing capacity ratio by a factor of 3.82 and a reduction of the settlement reduction factor by a factor of 0.813. The optimum length of the reinforcement was found to be 7.5 times the footing width.

KEY WORDS

Aluminum Foil Strips, Bearing Capacity Ratio, Linear Density of Reinforcement, Load-Settlement Behaviour, Relative Density and Square Footing.



تأثير كثافة التسليح على سلوك رمل مسلح تحت اساس مربع

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ملخص البحث

في هذه الدراسة، تم التحري عن سلوك رمل مسلح تحت اساس مربع. اجريت سلسلة من تجارب قوة التحمل على نموذج مختبري مصغر، ملئت بطبقات متجانسة من رمل ضعيف التدرج، والتي وضعت في حالة الكثافة المتوسطة باستخدام تقنية تمطير الرمل. سلحت الرمل بشرائط بعرض 40 ملم من رقائق الالمنيوم المتداولة في المنازل. الغرض من هذه الدراسة هي الاطلاع على سلوك منحنى القوة-الهبوط، و معرفة نسبة قوة التحمل و معامل تقليل هبوط الاساس، بتأمل تأثير طول شرائط التسليح، بتغير الكثافة الخطية للتسليح، عدد طبقات التسليح و عمق اعلى طبقة تسليح عن قاعدة الاساس.

بشكل عام اظهرت علاقة القوة-الهبوط، سلوك متشابه في كافة التجارب. عرفت فشل الاساس على اساس 10% من عرض الاساس. تمت عرض و مناقشة الطول الامثل لشرائط التسليح، الكثافة الخطية للتسليح، عدد طبقات التسليح و عمق اعلى طبقة تسليح عن قاعدة الاساس والتي تعطي تحسين في اقصى قوة التحمل و ادنى معامل تقليل هبوط الاساس. ان كل من قوة التحمل و تقليل معامل هبوط الاساس مقابل طول شرائط التسليح المختلفة عند بلوغ الفشل، اظهرت تحسين في قوة التحمل بنسبة 3.82 و تقليل معامل هبوط الاساس بنسبة 0.813. كما وجدت ان الطول الامثل لشرائط التسليح هي 7.5 مرة بقدر عرض الاساس.

كلمات مفتاحية

شرائط من رقائق الالمنيوم، نسبة قوة التحمل، الكثافة الخطية لعناصر التسليح، سلوك القوة-الهبوط، الكثافة النسبية و اساس مربع.



SYMBOLS:

- B Width of the square footing.
- BCR Bearing capacity ratio.
- L Length of the reinforcing strips.
- LDR Linear density of the reinforcement.
- N Number of reinforcing strip layers.
- NR Number of the reinforcing strips per each layer.
- N_γ Terzagh's bearing capacity factor.
- P Ultimate bearing load.
- S Settlement of the footing.
- Sh Horizontal spacing of the reinforcing strips.
- SIR Strength improvement ratio.
- SRF Settlement reduction factor.
- Sv Vertical spacing of the the reinforcing strips.
- U Depth of top layer of the reinforcing strips.
- γ Unit weight of the soil

1. INTRODUCTION



The footing resting on weak soils (i.e. soils having low bearing capacity) exhibits large settlements even under small loads, which can cause serious engineering problems leading to instability of the foundation and severe damage to the superstructure. Because of the population growth and increasing demand for extending the urban outspread, the reinforced soil is becoming a growing concern for geotechnical engineers dealing with foundation stability issues, especially above soft ground beds.

The modern concept of sand reinforcement was introduced by the French architect engineer Henry Vidal in 1966. Reinforced earth is defined as a construction material composed of granular materials and reinforcements placed in it. The reinforcing action requires frictional bond between the reinforcing strips and the soil particles with interlocking and adhesion properties. Hence free drainage granular soils were considered. The reinforcement can usually be any material possessing a substantial friction coefficient with the soil mass and capable of withstanding the tension force and deformation induced in the fill [7]. The resulting stable mass behaves monolithically, and can be used as earth retention and load supporting structures.

The main advantages of this technique are the low cost and rapid construction. Therefore it is an attractive and economical answer to many earth retention problems, such as retaining walls, bridge abutments, platform supporting structures, foundation slabs and dams [7]. The main purpose of sand reinforcement technique in load supporting structures is to increase the bearing capacity and reduce the settlement (i.e. improvement of the load bearing capacity and stiffness of the sand).

After the pioneer Henry Vidal studied the reinforced earth, much works have been conducted by several researchers on the analysis, field test and construction of reinforced sand models. During the past five decades, results of several studies have been performed that relate the evaluation of the ultimate and allowable bearing



capacities of shallow foundation supported by sand reinforced with multi-layered reinforcing strips. Many research works have been carried out on the effects of using reinforcement in soil such as geotextile and geogrid. Al-Aghbari M. (2007) showed that the increase in the bearing capacity of strip and circular footing reinforced with geocell is almost 8 times the unreinforced case [1]. Sireesh S. et. al. (2009) carried out tests on circular footing on geocell and the test results indicated improvement of the bearing capacity [14]. Gupta R. et. al. (2009) investigated circular footing rested on circular confinement with different diameter and different height and it was concluded that providing confinement improves bearing capacity [8]. Moghaddas S. et. al. (2010) investigated strip footing on sand with geocell and geotextile and they concluded improvement in the bearing capacity [12]. Kumar K. et. al. (2012) investigated square footing resting on geocell sand mattress and concluded that the bearing capacity increases with the provision of reinforcement below the footing [11]. Krishna A. et. al. (2014) carried out tests on square footing confined with steel casing and they concluded that the load carrying capacity of the footing increases due to confinement below the footing [9]. Gupta R. et. al. (2009) carried out an investigation on the confinement below the footing and the results have shown an increase in the bearing capacity with soil confinement [8].

In this study the results of laboratory model tests with square footing resting on homogenous reinforced sand bed were studied. The studied parameters were the effect of length of reinforcing strips on the load-settlement, bearing capacity ratio and settlement reduction factor using different linear density of the reinforcing strips, number of reinforcing strip layers and depth of the top layer of the reinforcing strips below the footing.



2. MATERIALS AND METHODS

2.1 MATERIALS

2.1.1 Soil

Soil from Khasa River in Kirkuk city was used in the laboratory model tests. Sieve analysis test was carried out on the soil, according to the British Standards and BSI 1377 [4], to determine the grain size distribution of the soil particles as shown in Fig. 1. It was found that the soil is poorly graded sand using Unified Soil Classification System-designation SP. Table 1 shows the properties of the sand.

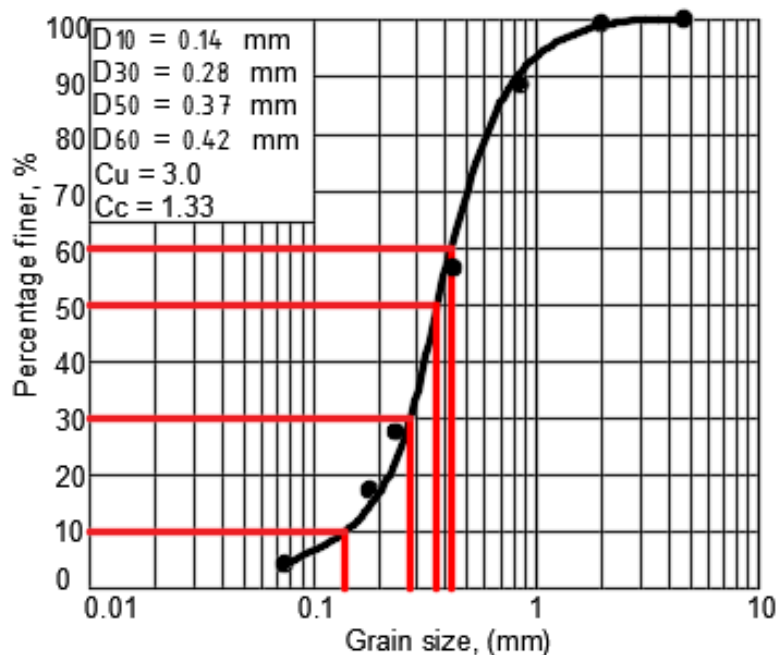


Figure (1) Grain size distribution of the sand



Table (1) Properties of sand used in the study

Property	Value	Test used
D10 (mm)	0.14	Sieve analysis test
D30 (mm)	0.28	
D50 (mm)	0.37	
D60 (mm)	0.42	
Coefficient of uniformity, C_u	3	
Coefficiency of curvature, C_c	1.33	Specific gravity test
Specific gravity, G_s	2.66	
Angle of internal friction between soil grains, ϕ (degree)	30	Direct shear test

The maximum density of the sand determined by means of compaction test was 16.98 kN/m^3 , while the minimum density of the sand found by jar test method was 14.32 kN/m^3 [10]. The corresponding values of the minimum and maximum void ratios were 0.567 and 0.858 respectively.

Sand raining technique was used to calibrate the density of the sand. The sand was rained through a mesh of $2.87 \times 2.87 \text{ mm}$ opening using different height of drops, which provides different values of placing density [10]. Fig. 2 shows the relation between height of drops, density and percentage relative density of the sand. It was decided to use medium dense state with density of 15.80 kN/m^3 throughout the investigation. This was obtained by 350 mm height of raining, which yielded in to a relative density of 60%.

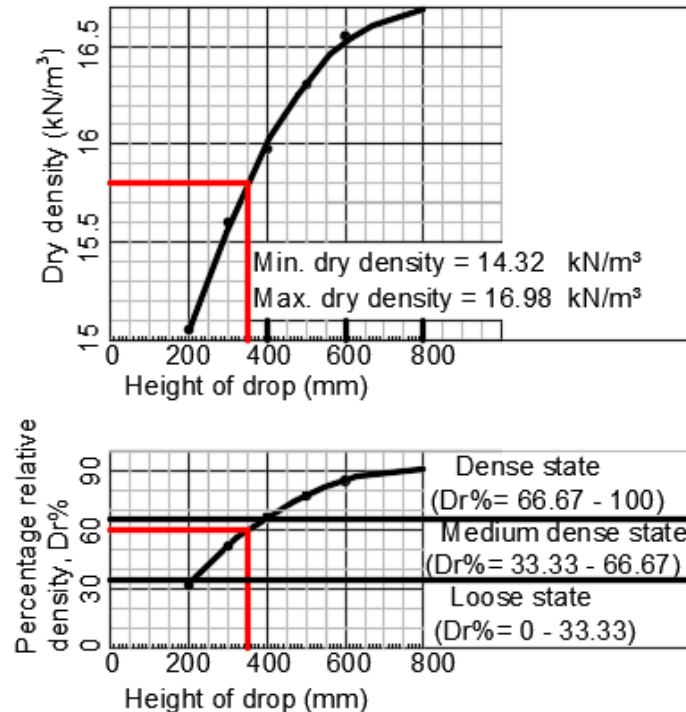


Figure (2) Sand density versus height of drops

2.1.2 Reinforcing Strip

The reinforcing strips used in this study were cut from rolls of household aluminium foil 0.05 mm thick and 40 mm wide. The breaking strength of the reinforcing strip was 50,000 kN/m². The angle of friction between the sand and the reinforcing strip was 25 degrees, determined by direct shear test using 60 x 60 mm shear box [5].

3. TEST METHODS

3.1 Testing apparatus

The testing apparatus generally consists of four main parts namely the box tank, the footing model, the loading and deformation system and the hopper raining tank. The overall view of the testing apparatus is shown in Fig. 3.

3.1.1 Box tank

The tests were all conducted in a well-stiffened wooden box of 450 mm deep x 550 mm wide x 1,350 mm length as internal dimensions, with 16.5 mm side and base thickness, supported by a rigid frame work 1,166 mm height to support the box as shown in Fig. 3. The box tank was strengthened in horizontal directions using a channel shaped steel section to avoid lateral deformation / bulging of tank walls during filling of the sand bed and loading conditions.

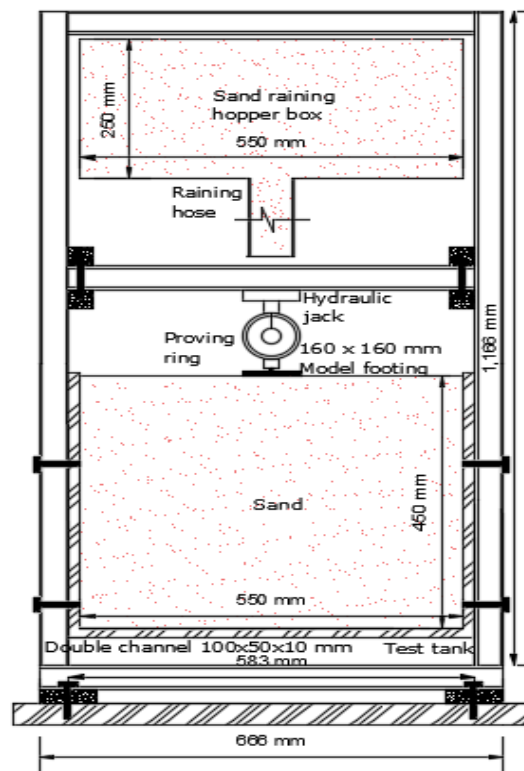


Figure (3) Testing apparatus

3.1.2 Footing model



The footing dimension (B) was 160 mm square side rigid steel plate 10 mm thick as shown in Fig. 3. The base of the model footing was roughened by covering it with epoxy glue and rolling it in sand [3]. In order to provide vertical loading alignment, a small hemi-spherical indentation was made at the centre of the footing model to accommodate a ball bearing through which vertical loads were applied to the footing uniformly. Such arrangement produced a hinge, which allows the footing to rotate freely as it approaches the failure and eliminates any potential moment transfer from the loading fixture to the footing.

3.1.3 Loading and deformation system

Vertical loads were applied by means of a motorised 3 tones capacity hand-operated hydraulic jack at a constant rate of 15 mm/hr and by using a pre-calibrated load ring as shown in Fig. 3. The settlement of the footing was measured by means of two dial gauges placed on the footing surface.

3.1.4 Raining hopper tank

The sand raining hopper box tank was 550 x 1000 mm in plain view and 250 mm in depth and it was made of wood. The outlet of the hopper was connected to a flexible raining hose to control the sand raining easily. The raining hose was of the sliding type. It consists of two aluminium pipes, one slides inside the other, to control the raining height. A stainless steel mesh of 2.87 x 2.87 mm square opening was attached to the end of the hose in order to control the rate of flowing sand as shown in Fig. 3.

3.2 Testing program

Fig. 4 and Fig. 5 represent the layout and configuration of the reinforcing strips under different reinforcing conditions used in this study.

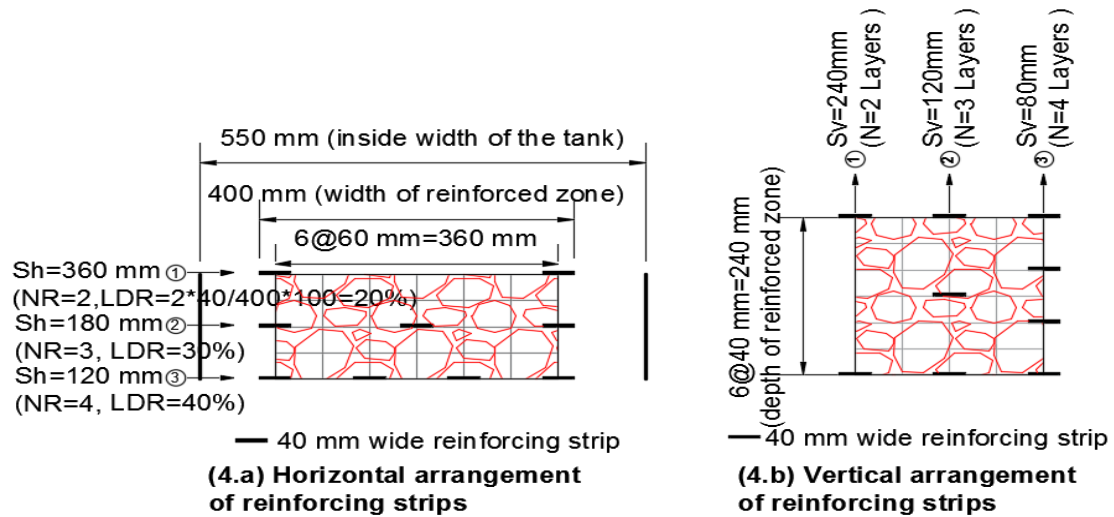


Figure (4) Horizontal and vertical layout of the reinforcement

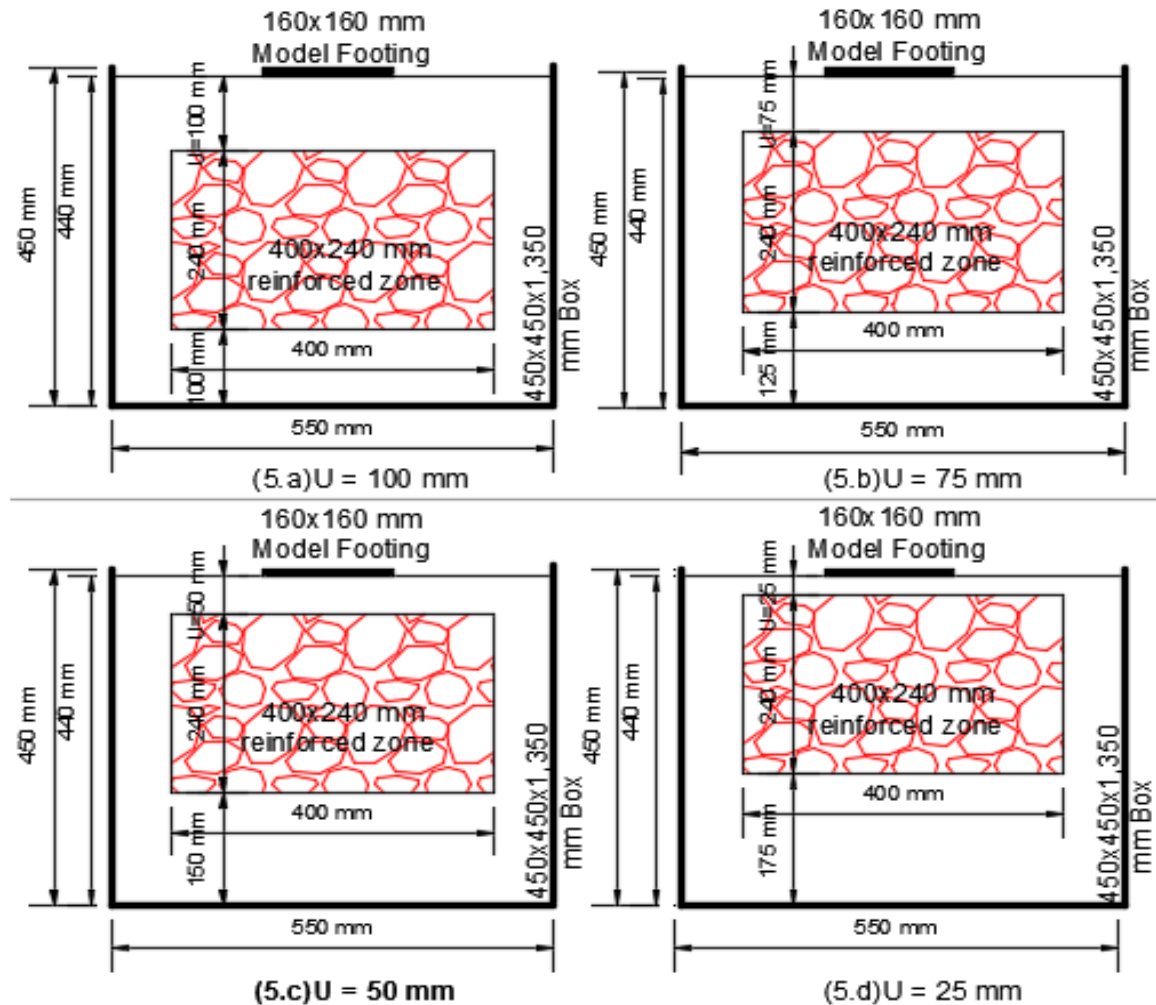


Figure (5) Layout of depth of top layer of the reinforcement

The main parameters concerned in this study were the effect of length of the reinforcing strips on the load-settlement, bearing capacity ratio and settlement reduction factor relationships, using the following cases:

- Different linear density of the reinforcing strips (LDR %).
- Different number of the reinforcing layers (N).
- Different depth of the top layer of the reinforcing strips below the footing (U).

While the other parameters such as the size of the footing, reinforcement properties and the relative density of the fill were kept constants.

The testing program was divided into two groups as follows:



Group I: One test was done on unreinforced sand.

Group II: Thirty two tests were done on reinforced sand, which divided into three main series as presented in Table 2.

Table (2) Testing program

Series I: Different percentage of linear density of the reinforcing strips, LDR%									
U (mm)	N (Layers)	Sv (mm)	LDR%	NR (Reinf. / layer)	Sh mm)	L (mm)			
50	4	80	20	2	360	400	700	1,000	1,300
			30	3	180	400	700	1,000	1,300
			40	4	120	400	700	1,000	1,300
Series II: Different number of reinforcing strip layers, N									
U mm)	LDR%	NR (Reinf. / Layer)	Sh (mm)	N (Layers)	Sv (mm)	L (mm)			
50	40	4	120	2	240	400	700	1,000	1,300
				3	180	400	700	1,000	1,300
				4	120	400	700	1,000	1,300
Series III: Different depth of top layer of the reinforcing strips below the footing, U									
N (Layers)	Sv (mm)	LDR%	NR (Reinf. / Layer)	Sh (mm)	U (mm)	L (mm)			
4	80	40	4	120	25	400	700	1,000	1,300
					50	400	700	1,000	1,300
					75	400	700	1,000	1,300
					100	400	700	1,000	1,300

3.3 Test procedure



The testing procedure started by placing specified layer of the sand over base of the box according to the layout and configuration of the reinforcing strips that shown in Fig. 5, then the first layer of reinforcing strips was laid. The sand was placed at the proposed density of 15.80 kN/m^3 by keeping a constant height of 350 mm above the sand surface, which controlled by sliding the hose up and down. This was easily done with the aid of guide marker along the outer part of the hose. In order to obtain a uniform and level surface, the raining hose was continuously moved forward and backward and in transverse direction. When the level of the reinforcing strips was reached, levelling the sand surface was performed to give accepted contact between the reinforcing strips and the sand bed. After laying the last layer of reinforcement a sand layer was placed representing the depth of the top layer of the reinforcement below footing, then the footing was placed and the two dial gauges were placed on the opposite sides of the footing surface to measure the settlement [7]. The load was applied in small increments until reaching failure using a hydraulic jack. Each load increment was maintained constant until the footing settlement had stabilized. The failure load was defined as the settlement of the footing equal to 10% of the footing width. The vertical movement was recorded and the entire load settlement curve at failure was obtained.

4. RESULTS AND DISCUSSION

A series of laboratory model tests were conducted to study the effect of reinforcing strip length on the behaviour of the load-settlement curve and to find the optimum reinforcing strip length required to obtain the maximum bearing capacity. The reinforcing strip length was varied from 400 mm to 1,300 mm in increment of 300 mm.

A reference test was performed for the case of unreinforced soil. The measured ultimate load P_0 and the associated ultimate settlement S_0 for the unreinforced sand was found to be 652 N and 16 mm respectively, which shows a close agreement with the theoretical ultimate load of 647.2 N calculated from Terzaghi's equation:

$$q_u = 0.5 \gamma B N_\gamma \dots\dots\dots (1)$$



Where:

γ is unit weight of the soil.

B is width of the footing.

N_γ is Terzaghi bearing capacity factor, which depends on the angle of internal friction of the soil (ϕ). For $\phi = 30$ degrees, $N_\gamma = 20.0$

In order to get a quantitative assessment of the extent of soil improvement, the improvement due to the provision of the reinforcement can be shown in non-dimensional strength improvement ratio, which is defined as the ratio of the ultimate bearing load of the reinforced sand to ultimate bearing load of the unreinforced sand or it is known as bearing capacity ratio (BCR).

$$BCR = P / P_0 \dots\dots\dots (2)$$

Where P and P_0 are the ultimate bearing load for reinforced and un-reinforced sand tests respectively, at any desired settlement.

The improvement due to the inclusion of the reinforcement layers in sand, in terms of reduction in footing settlement, can be known using the settlement reduction factor (SRF) parameter, which is defined as:

$$SRF = (S_o - S_r) / S_o \dots\dots\dots (3)$$

Where S_r and S_o are the settlement of reinforced and un-reinforced sand bed respectively, at the same pressure of S_o .

The test results of the laboratory model are presented with a discussion highlighting the effects of different parameters according to the test program as shown in Table 3.

The calculation of the bearing capacity ratio for LDR=40%, N=4 layers, U=50 mm and L=1,300 mm gives:

$$BCR = 2.492 / 0.652 = 3.82$$

The calculation of the settlement reduction factor for LDR=40%, N=4 layers, U=50 mm and L=1,300 mm gives:

$$SRF = (16 - 3.0) / 16 = 0.813$$

The presentation of all results details would make the paper lengthy. Therefore, only a calculation of one result is presented. Table 4 shows the results of the ultimate



pressure P with the associated displacement S for $LDR=40\%$, $N=4$ layers, $U=50$ mm and different length of the reinforcement.

As a result of model tests, values of bearing loads and displacements of the footing were obtained. Recorded data were used to plot the load-settlement relation for each considered model. Typical variations of bearing load versus footing settlement with and without soil reinforcement for the typical model test are presented in Fig. 6.

It can be observed that the reinforcement appreciably improves the bearing resistance of the footing as well as the stiffness of the foundation bed. It is obvious that the mode of failure is a general shear failure and the similar trend was observed in all the tests, in which a peak value can be observed, after which the footing collapses and exhibits strain softening, where the load decreases then become constant with increasing settlement.



Table (3) Overall results of the study according to program layout and configuration

U = 50 mm, N = 4 layers, different L with different LDR%							
#	LDR%	L (mm)	P (kN)	BCR	S (mm)	SRF	Notes
1	20	400	0.715	1.10	13.5	0.156	Failure mode was by reinf. Pulled-out.
2		700	0.812	1.25	9.9	0.381	Failure mode was by reinf. Pulled-out.
3		1,000	1.169	1.79	6.5	0.594	
4		1,300	1.291	1.98	6.0	0.625	
5	30	400	0.728	1.12	12.6	0.213	Failure mode was by reinf. Pulled-out.
6		700	0.910	1.40	8.8	0.450	
7		1,000	1.351	2.07	5.0	0.688	
8		1,300	1.560	2.39	4.0	0.750	Failure mode was by reinf. Broken in tension.
9*	40	400	0.810	1.24	10.1	0.375	
10*		700	1.166	1.79	6.2	0.613	
11*		1,000	2.068	3.17	4.0	0.750	Failure mode was by reinf. Broken in tension.
12*		1,300	2.492	3.82	3.0	0.813	Failure mode was by reinf. Broken in tension.
U = 50 mm, LDR = 40%, different L with different N							
#	N (layer)	L (mm)	P (kN)	BCR	S (mm)	SRF	Notes
13	2	400	0.712	1.09	13.8	0.156	Failure mode was by reinf. Pulled-out.
14		700	0.844	1.29	10.8	0.381	
15		1,000	0.941	1.44	7.1	0.594	
16		1,300	1.003	1.54	5.4	0.625	
17	3	400	0.746	1.14	12.0	0.213	
18		700	1.040	1.60	9.0	0.450	
19		1,000	1.956	3.00	5.0	0.688	
20		1,300	2.274	3.49	4.0	0.750	
21*	4	400	0.810	1.24	10.0	0.375	
22*		700	1.166	1.79	6.2	0.613	
23*		1,000	2.068	3.17	4.0	0.750	Failure mode was by reinf. Broken in tension.
24*		1,300	2.492	3.82	3.0	0.813	Failure mode was by reinf. Broken in tension.
N = 4 layers, LDR = 40%, different L with different U							
#	U (mm)	L (mm)	P (kN)	BCR	S (mm)	SRF	Notes



25	25	400	0.725	1.11	13.0	0.188	Failure mode was by reinf. Pulled-out.
26		700	0.808	1.24	10.0	0.375	
27		1,000	1.175	1.80	7.5	0.531	
28		1,300	1.292	1.98	7.0	0.563	
29*	50	400	0.810	1.24	10.0	0.375	
30*		700	1.166	1.79	6.2	0.613	
31*		1,000	2.068	3.17	4.0	0.750	Failure mode was by reinf. Broken in tension.
32*		1,300	2.492	3.82	3.0	0.813	Failure mode was by reinf. Broken in tension.
33	75	400	0.730	1.12	11.6	0.275	Failure mode was by reinf. Pulled-out.
34		700	0.980	1.50	8.1	0.494	
35		1,000	1.700	2.61	5.0	0.688	
36		1,300	2.100	3.22	3.6	0.775	
37	100	400	0.800	1.23	12.0	0.250	Failure mode was by reinf. Pulled-out.
38		700	0.906	1.39	9.5	0.406	Failure mode was by reinf. Pulled-out.
39		1,000	1.450	2.22	5.9	0.631	
40		1,300	1.650	2.53	6.9	0.719	
Note: Tests number marked with * are same tests.							



Table (4) Results of the ultimate load P and footing settlement for unreinforced and reinforced sand with depth of top layer of reinforcement $U = 50$ mm, number of reinforcement layers $N = 4$ layers, linear density of reinforcement $LDR = 40\%$ and different length of reinforcement

Settlement S (mm)	Ultimate bearing load, P_0 (kN) for unreinforced sand (reference test)	Ultimate bearing load, P (kN) for reinforced sand			
		Length of the reinforcing strips, L (mm)			
		400	700	1000	1300
0	0.000	0.000	0.000	0.000	0.000
2	0.079	0.145	0.214	0.344	0.468
4	0.165	0.286	0.426	0.681	0.919
6	0.260	0.420	0.626	1.004	1.337
8	0.345	0.543	0.800	1.305	1.707
10	0.437	0.650	0.958	1.574	2.016
12	0.535	0.736	1.076	1.800	2.255
14	0.615	0.792	1.148	1.972	2.415
16	0.652	0.810	1.166	2.068	2.492
18	0.637	0.796	1.152	2.054	2.478
20	0.618	0.777	1.133	2.035	2.459
22	0.600	0.759	1.113	2.017	2.441
24	0.593	0.752	1.108	2.010	2.434

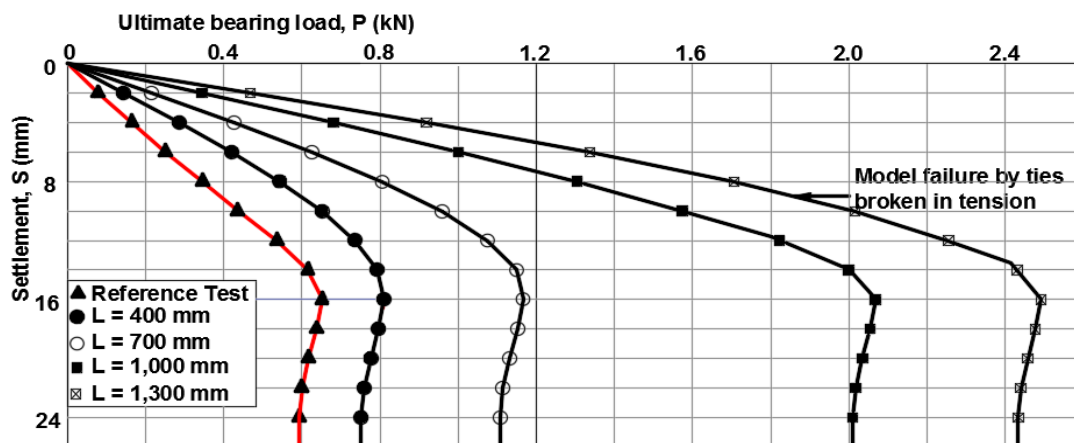


Figure (6) Load-settlement relation for reinforced sand with $LDR = 40\%$, $N = 4$ layers, $U = 50$ mm and different length of reinforcement



The ultimate load in any test was defined as the load corresponding to the beginning of the strain-softening portion of the curve, which was found approximately to be 16 mm ($S/B=10\%$).

For small settlement (e.g. $S=8$ mm corresponding to $S/B=5\%$), the ultimate load was not reached. Hence the BCR for the low settlement situation represents a comparison of the non-failure condition. For large settlement (e.g. S greater than 16 mm corresponding to S/B greater than 10%), the footing had actually failed, and the BCR values for these large settlements represent a comparison of the failure condition. Fig. 6 also shows, that the soil reinforcement process improved the bearing load from 0.652 kN for the unreinforced case to 2.492 kN for the reinforced soil with $U=25$ mm, $LDR=40\%$, $N=4$ layers and $L=1,300$ mm. In addition, it was shown that the tests with the above mentioned parameters, failed due to ties broken in tension for the upper layer, at location approximately under the edges of the footing.

For the tests with low density of reinforcements (i.e. $L=400$ and 700 mm, and $U=25$ mm, $LDR=20\%$ and $N=2$ layers), failure had occurred due to ties pulling out for the upper layer after overcoming the soil-tie friction resistance.

4.1: Effect of the studied parameters

The effect of reinforcing strip length on the BCR and SRF was divided into three main series as follows:

4.1.1 Series I: Different LDR%

Figures 7 to 10 show the effect of reinforcing strip length on the load-settlement relation behaviour for different LDR%. Fig. 11 shows different BCR- L relations for $S/B=10\%$ at failure condition. The shape of the curves suggested that at any LDR%, three stages could be identified for the failure mechanism of the footing which were L less than 500 mm, L between 500 mm to 1,200 mm and L greater than 1,200 mm. For L less than 500 mm and greater than 1,200 mm, the rate of increase of BCR with increasing the length of the reinforcing strip was very low with little



difference between BCR. However, the rate of increase for L between 500 mm to 1,200 mm was steeper and effectively shows that there was a little change in BCR with increasing the length of the reinforcing strips. Fig. 12 shows different SRF- L relations. The shape of the curves for L less than 1,200 mm suggested that the rate of the increase of SRF values with the increasing length of the reinforcing strip was steep and there was a large difference between SRF. However, the rate of increase for L greater than 1,200 mm was very low.

The test results show, that the models with low linear density of reinforcements (i.e. $LDR=20\%$), leads to reduction in the load carrying capacity of the footing indicated by softening in the slope of the load-settlement response. The behaviour of the load-settlement was similar to the unreinforced sand and there was no noticeable change in both BCR and SRF. In addition, it was shown that the load bearing pressure due to high linear density of reinforcement increased with long strip lengths. This is due to the frictional resistance at the interface of the sand and reinforcement, which may have prevented the soil mass from shearing under vertical applied load.

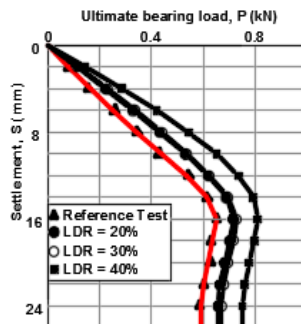


Figure (7) Load-settlement relation for (U=50 mm, N=4 Layers, L=400 mm and different LDR)

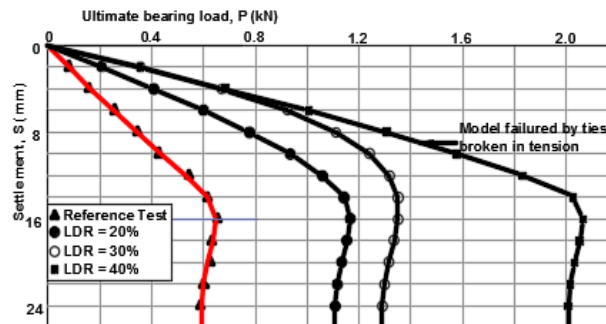


Figure (9) Load-settlement relation for (U=50 mm, N=4 Layers, L=1,000 mm and different LDR)

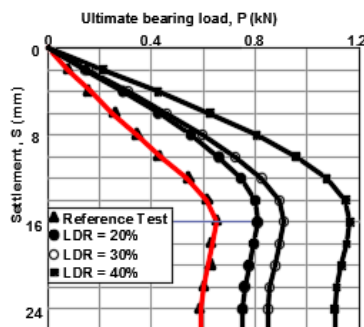


Figure (8) Load-settlement relation for (U=50 mm, N=4 Layers, L=700 mm and different LDR)

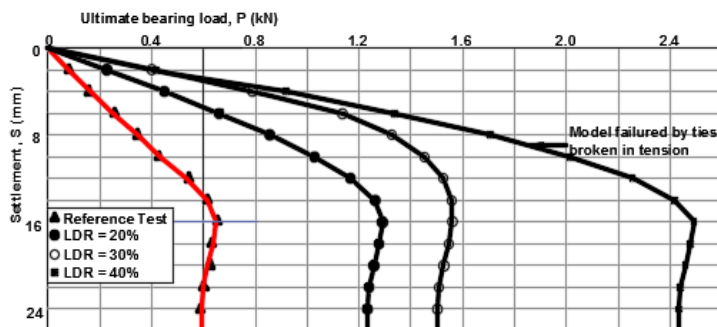


Figure (10) Load-settlement relation for (U=50 mm, N=4 Layers, L=1,300 mm and different LDR)

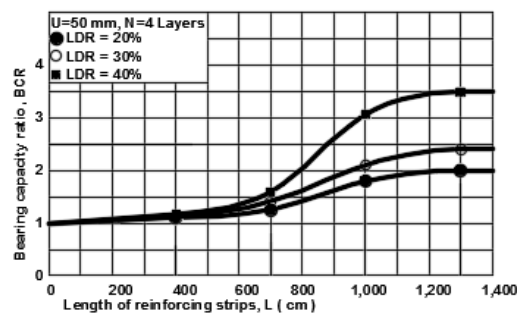


Figure (11) Bearing capacity ratio versus length of reinforcing strips, for (U=50 mm, N=4 layers and different LDR%)

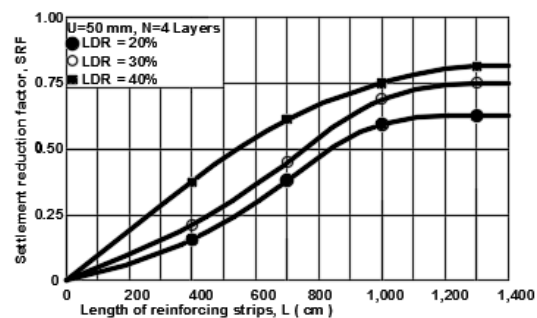


Figure (12) Settlement reduction factor versus length of reinforcing strips, for (U=50 mm, N=4 layers and different LDR%)

4.1.2 Series II: Different N



In order to investigate the effect of reinforcing strips length with different reinforcement layers on the footing response, tests were carried out using three different layers. Figures 13 to 16 show the effect of reinforcing strip length on the load-settlement relation behaviour for different N.

Figure 17 shows different BCR-L relations for $S/B=10\%$ at failure condition. The shape of the curves suggested that at any N, three stages could be identified for the failure mechanism of the footing for L less than 500 mm, L between 500 mm to 1,200 mm and L greater than 1,200 mm. For L less than 500 mm and greater 1,200 mm, the rate of increase of BCR with increasing the length of the reinforcing strip was very low, with little difference between BCR. However, the rate of increase for L between 500 mm to 1,200 mm was steeper and effectively shows that there was little change in BCR with increasing the length of the reinforcing strips. The trend confirms the conclusion that the greatest benefit of reinforcement can be obtained at N=4 layers. It may be clearly observed that with increasing the number of reinforcement layers, both stiffness and bearing pressure considerably increase, irrespective of the void embedded depth.

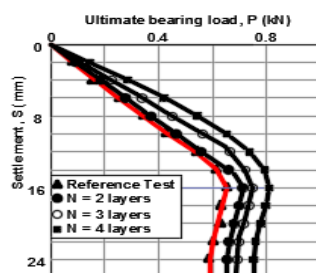


Figure (13) Load-settlement relation for (U=50 mm, LDR=40%, L=400 mm and different N)

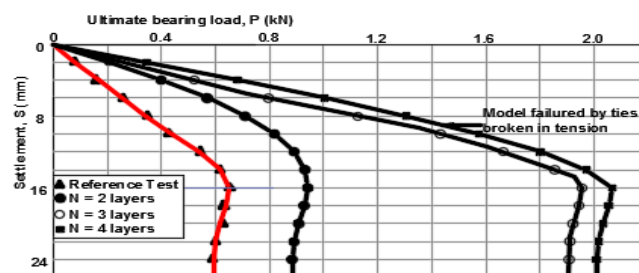


Figure (15) Load-settlement relation for (U=50 mm, LDR=40%, L=1,000 mm and different N)

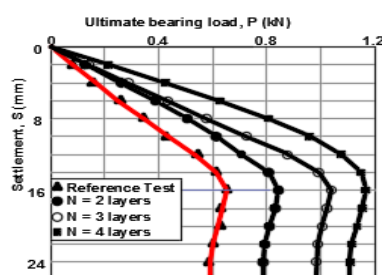


Figure (14) Load-settlement relation for (U=50 mm, LDR=40%, L=700 mm and different N)

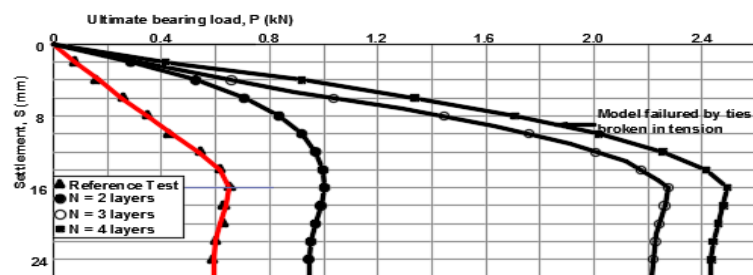


Figure (16) Load-settlement relation for (U=50 mm, LDR=40%, L=1,300 mm and different N)

Figure 18 shows different SRF-L relations. The shape of the curves suggested that at any N and for L less than 1,200 mm, the rate of the increase of SRF with increasing the length of the reinforcing strip was steep with large difference between SRF. However, the rate of increase for L greater than 1,200 mm was very low. With increasing length of the reinforcing strips, the change in the footing settlement reduction factor SRF are insignificant and this number may be due to the optimum length of the reinforcement.

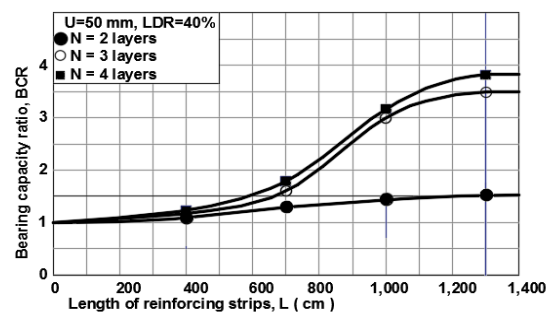


Figure (17) Bearing capacity ratio versus length of reinforcing strips, for (U=50 mm, LDR=40% and different N)

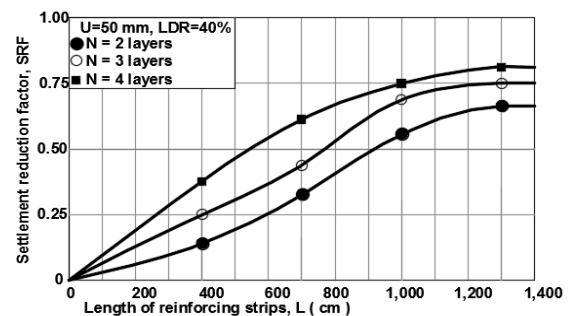


Figure (18) Settlement reduction factor versus length of reinforcing strips, for (U=50 mm, LDR = 40% and different N)

As generally, the test results shows that the models with low number of reinforcement layers (N=2 layers) leads to reduction in the load carrying capacity of the footing indicated by softening in the slope of load-settlement curve. The behaviour of the load-settlement was similar to that of unreinforced sand with no noticeable changes in BCR an SRF. The results also shows that the load bearing pressure with high number of reinforcement layers increased with long strip lengths. This is due to the frictional resistance at the interface of the sand and the reinforcement, which would have prevented the soil mass from shearing under vertical applied load.

4.1.3 Series III: Different U

Fig. 19 to 22 show the effect of reinforcing strip length on the load-settlement curve behaviour for different U.

Figure 23 shows different BCR-L relations for $S/B=10\%$ for failure condition. The shape of the curves suggested that at any U , three stages could be identified for the failure mechanism of the footing for L less than 500 mm, L between 500 mm to 1,200 mm and L greater than 1,200 mm. For L less than 500 mm and greater than 1,200 mm, the rate of increase of BCR with increasing the length of the reinforcing strip was very low with little difference between BCR. However, the rate of the increase for L between 500 mm and 1,200 mm was steeper and effectively showing that there was a little change in the BCR with increasing length of the reinforcing strips.

Figure 24 shows different SRF-L relations. The shape of the curves suggested that at any U and for L less than 1,200 mm, the rate of the increase of the SRF with increasing the length of the reinforcing strip was steep with large difference between SRF. However, the rate of increase for L greater than 1,200 mm was very low.

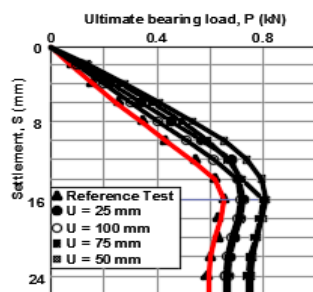


Figure (19) Load-settlement relation for (LDR=40%, N=4 Layers, L=400 mm and different U)

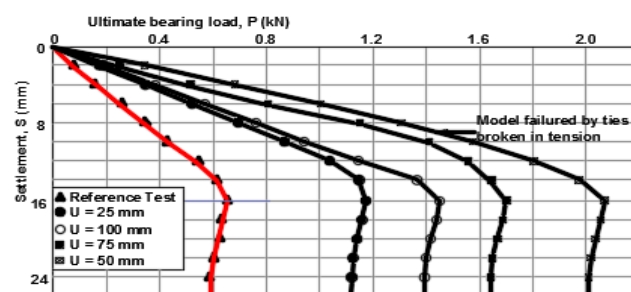


Figure (21) Load-settlement relation for (LDR=40%, N=4 Layers, L=1,000 mm and different U)

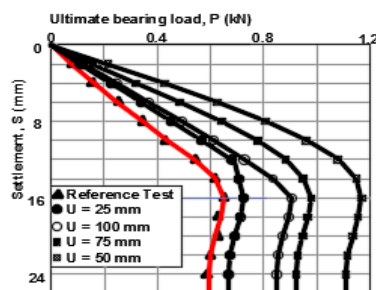


Figure (20) Load-settlement relation for (LDR=40%, N=4 Layers, L=700 mm and different U)

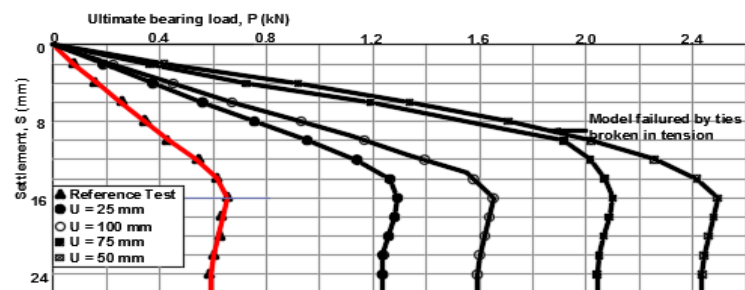


Figure (22) Load-settlement relation for (LDR=40%, N=4 Layers, L=1,300 mm and different U)

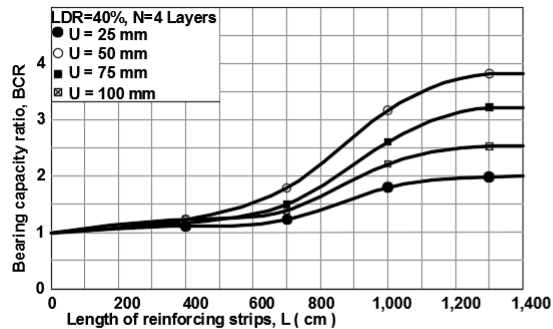


Figure (23) Bearing capacity ratio versus length of reinforcing strips, for (N=4 layers, LDR=40% and different U)

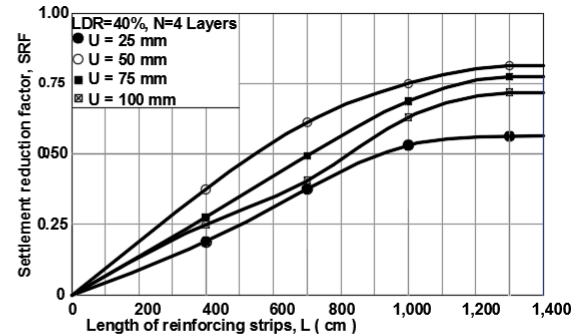


Figure (24) Settlement reduction factor versus length of reinforcing strips, for (N=4 layers, LDR=40% and different U)

As overall view, the test results showed that the models with depth of top layer of reinforcement (U less than 25 mm and U greater than 75 mm) leads to reduction in the load carrying capacity of the footing indicated by softening in the slope of pressure-settlement response. The behaviour of the load-settlement was similar to the unreinforced sand and there was no noticeable change in both BCR and SRF. The results also show that the load bearing pressure of U=50 mm with long strip lengths is optimum. This is due to the frictional resistance at the interface of the sand and the reinforcement, which would have prevented the soil mass from shearing under vertical applied load.

The significant increase in the bearing capacity magnitude of the footing can be explained as follows. When the footing is loaded, the reinforcement resists the lateral displacements of the soil particles underneath the footing leading to a significant decrease in the vertical settlement and hence improving the bearing capacity. For short length of the reinforcement and as the pressure is increased, the plastic state is developed initially around the edges of the footing and then spreads downward and outward.



The variation of the BCR at different normalized depths to the top of the reinforced zone for $N=3$ layers, $LDR=40\%$ and different L with various U is shown in Fig. 23. It is interesting to notice that increasing the depth of the top layer of the reinforcement leads to an additional improvement in the bearing capacity magnitude up to a specific value of U , and then the BCR remains constant with the increase of the length of reinforcing strips. The initial increase in the BCR with U can be explained with the fact that the footing pressure spreads with increasing the depth acting over a larger area of the reinforced-sand system. With a further increase in the depth of the top layer of the reinforcement, the soil between the footing and the reinforced zone deforms laterally and, therefore, the vertical settlement increases and the BCR decreases. Based on these results, it is recommended that the depth of the top layer of the reinforcement should be at a depth of $0.3B$ from the bottom of the footing to get the maximum increase in the BCR. A similar recommendation was given by Dash S. et. al. (2001) with using a geo-cell mattress to confine sand underneath a footing [6].

5. CONCLUSIONS

Based on the results discussed in this study, the following conclusions are gained:

1. The results indicated that substantial improvement in the footing system performance can be achieved with the provision of reinforcement .The reinforced sand system behaves much stiffer and causes less settlement than the unreinforced sand system.
2. The load versus footing deformation response of the reinforced sand bed was much better than the unreinforced case. This was due to the frictional resistance at the interface of the sand and the reinforcement, which would have prevented the soil mass from shearing under vertical applied load.



3. Beginning of the strain-softening portion for the load-settlement curve, which was approximately 16 mm (equivalent to $S/B=10\%$), can be considered as the ultimate failure condition.
4. Provision of reinforcement layers improves the bearing capacity ratio of the model footing and reduces the settlement reduction factor.
5. The reinforced sand with high density of reinforcement had the best parameters such the friction between the soil and the material surface than low density reinforced sand.
6. The footing load bearing capacity under high density reinforcement becomes about 4 times compared to the unreinforced sand.
7. From the overall performance of the model footing (i.e. both strength and settlement aspects), the optimum location of the reinforcement is about $0.33B$ below the base of the footing within the effective reinforcement zone.
8. It is concluded that the use of the reinforcing strip length less than $3 B$ was inconvenient because it leads to small BCR even with large LDR% and reinforcement layers. While the length of L greater than $3 B$ allows the use of small LDR% and reinforcement layers and leads to obtain large BCR.
9. The use of about $7.5 B$ as optimum length of reinforcing strip length produces a maximum BCR and any additional length is wasted for practical application consideration.
10. Different BCR- L relations showed improvement of BCR by a factor of 1.5 to 4. These relations can be used as guide charts to predict the amount of BCR and reinforcing strip length, if the other parameters of reinforcing strips are selected and vice versa.

RECOMMENDATION

The following recommendations are suggested:

1. It is recommended to use circular footing.
2. It is recommended to use different types of reinforcement.



3. It is recommended to use different density state of the sand (i.e. different values of percentage of relative density)

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