STRENGTHENING OF LOADED FOOTING-SOIL SYSTEM

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ABSTRACT

The applications of the concept of soil reinforcement were diverted in this study to a new one which is, strengthening of a critically stable foundation. Plate loading tests on sand were conducted in laboratory to investigate the effect of length of reinforcing elements, pre-reinforcing load acting on the footing, distance between reinforcing elements and edge of the footing, number of reinforcing elements and characteristics of sand. To get the best benefit of soil reinforcement, it was found that the length of the elements below foundation level should be equal twice the footing width, the elements should be placed as early as possible before the commencement of failure surface underneath the footing and as close to the footing as possible with adequate number of elements and the relative density of sand should be big.

NOTATIONS

γ	Unit weight of the soil.
σ	Bearing stress at footing-soil interface.
B	Diameter of the footing.
L	Length of the reinforcing element.
x	Distance between the reinforcing elements and edge of the footing.
δ	Vertical displacement of the footing.
d	Diameter of the reinforcing element.
D_r	Relative density of the sand bed.
ϕ	Angle of shearing resistance of the sand.
$A_{sur.}$	Surface area of the reinforcing elements
A_{cs}	Cross section area of the footing
B.C.R	The ratio between the bearing stress of the reinforced and unreinforced soil.

INTRODUCTION

The utilization of reinforcing material to increase the bearing capacity of soil is now widely used in road sub-bases, railways and soil replacement techniques, Binquet and Lee (1975), Mosaid and Edward (1978), Abdrabbo (1979), Mahmoud and Abdrabbo (1987), Mahmoud and Abdrabbo (1989), Mahmoud (1988) and Giroud and Noritrary (1981). The controlling factor of soil reinforcement is to use reinforcing material with sufficient interface-soil friction that can inhibit the development of tensile strains in the soil and thereby reinforcing it. The proper directions of soil reinforcement elements are the directions of principle tensile strain planes, McGown et al (1978). The greatest drawback of soil reinforcement technique is presented by the removal of the in-situ soil from the site to the desired depth and backfilling it again in horizontal layers compacted to the desired density with inclusions. In fact, the idea of using the reinforced soil concept to increase the bearing capacity of soil is not a new idea and most of the applications are devoted for increasing the bearing capacity of soil before the application of loads, that is to say, during construction phase.

In the present study, the concept is diverted to a new application which is strengthening of existing foundations to safeguard critically stable buildings. In order to simulate this new concept, loading tests have been performed on a surface circular footing resting on sand deposit, up to a predetermined percentage of the failure load, then, the sand is reinforced by vertical rods and the test is completed up to failure in footing-soil system. The studied parameters in this research are: length of reinforcing rods, pre-reinforcing load acting on the footing as percentage of the failure load, distance between soil reinforcement elements and edge of the footing, number of reinforcing elements and relative density of the soil. Table (1) shows the test programme in the present work.

Table 1. Test programme

Group No.	Test No.	L/B	x/B	Load Ratio	No. of Reinf. bars
I	I-1	-	-	-	-
	I-2	2.0	1.0	0.0	8
	I-3	2.0	1.0	0.25	8
	I-4	2.0	1.0	0.50	8
	I-5	2.0	1.0	0.75	8
II	II-1	0.5	1.0	0.50	8
	II-2	1.0	1.0	0.50	8
	II-3	2.0	1.0	0.50	8
	II-4	3.0	1.0	0.50	8
	II-5	4.0	1.0	0.50	8
III	III-1	2.0	0.5	0.50	8
	III-2	2.0	1.0	0.50	8
	III-3	2.0	2.0	0.50	8
	III-4	2.0	3.0	0.50	8
IV	IV-1	2.0	1.0	0.50	4
	IV-2	2.0	1.0	0.50	8
	IV-3	2.0	1.0	0.50	12
	IV-4	2.0	1.0	0.50	16
V	V-1	-	-	-	-
	V-2	1.0	1.0	0.50	8
	V-3	2.0	1.0	0.50	8
	V-4	3.0	1.0	0.50	8
	V-5	4.0	1.0	0.50	8

Table 1. Contd.

Group No.	Relative density %	Ultimate bearing stress σ, KN/m^2	BCR	Notes
I	90	294.53	1.00	Without reinf.
	90	399.36	1.356	
	90	362.54	1.231	
	90	356.93	1.212	
	90	346.32	1.176	
II	90	330.72	1.123	
	90	370.03	1.256	
	90	356.93	1.212	as in test No. I-4
	90	359.42	1.220	
	90	352.56	1.197	
III	90	373.15	1.267	
	90	356.93	1.212	as in test No. I-4
	90	345.70	1.174	
	90	338.21	1.148	
IV	90	336.96	1.144	
	90	356.93	1.212	as in Test No. I-4
	90	436.80	1.480	
	90	461.76	1.568	
V	38	149.76	1.00	without reinf.
	38	160.38	1.071	
	38	169.73	1.133	
	38	168.48	1.125	
	38	169.73	1.133	

TEST EQUIPMENT AND PROCEDURE

Loading tests on a circular footing model resting on the surface of sand subgrades, were performed in cylindrical steel rigid bin; 750 mm in diameter and 600 mm high. The general test set up is shown in Figure (1). The load was applied using a lever and guiding system and recorded with the help of a calibrated proving ring. The lever is made of a prefabricated steel channel No. 10 connected to u-shape steel frame via ball bearings and resting freely on ball bearing attached to the top of the loading shaft, which is machined from steel rod 50 mm in diameter.

The displacement of the footing was recorded by two dial gauges; 0.01 mm accuracy fixed rigidly to the soil bin using magnetic bases, whereas their tips are resting on the surface of the footing. During loading tests, the difference between readings of the two dial gauges, were kept to be within 1 % of the mean values, to accept the test results.

Model footing 100 mm in diameter, was machined from a steel plate 10 mm thick. The reinforcing elements, were made of galvanized steel rods having a diameter of 6mm.

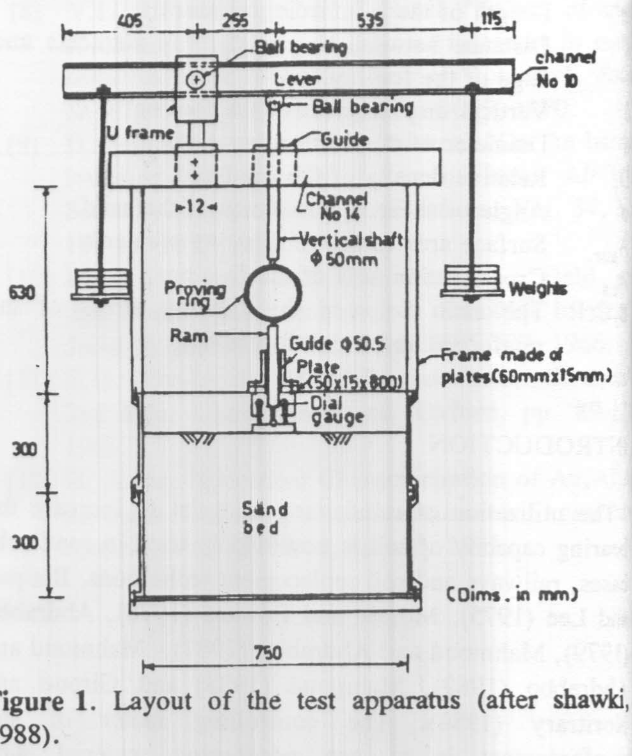

Figure 1. Layout of the test apparatus (after shawki, 1988).

The loads transferred from the lever to the footing, were recorded using calibrated proving ring; 49 N sensitivity. The loads were checked by the principles of statics using the lever arm ratio and no differences what so ever were observed.

The cohesionless soil beds were prepared by pouring standard yellow silicious sand of medium size in layers through a funnel, held at a constant height; 300 mm above the surface, each layer was compacted using an electrical hand vibrator. The uniformity coefficient and the effective size of the sand are, 2.513 and 0.215 mm respectively. The surface of the test bed was properly leveled and checked by a spirit level. The dry density of the sand bed was found to be 17.50 KN/m^3 (D_r = 90%); the corresponding angle of shearing resistance determined using triaxial apparatus is 43^o.

Some tests were carried out on sand beds having a dry unit weight of 15.70 KN/m^3 (D_r = 38 %); the corresponding angle of shearing resistance is 34^o as determined using triaxial apparatus. The homogeneity of the sand bed was controlled by weighing the required amount of san to place for each layer, also, four special small wooden boxes of 90 cm^3 volume, placed at different depths in the sand bed, were used to measure the sand density and to check the homogeneity of the formed bed. Furthermore, weighing all of the sand in the soil bin, enables calculating the global density of the sand bed. The difference between the density measured at the four points using the wooden boxes, was kept under the level 1 % and the difference between the global density and the average density at the four points was kept also under the level 1.5 %, otherwise, the sand bed is refused and the test is repeated again.

After placing and forming the sand bed, the footing was loaded incrementally up to a predetermined percentage of the failure load. The test load was kept constant for a few minutes and the reinforcing elements were pushed vertically around the footing to the required depth, then, the loading test was completed to failure. A reference loading test was conducted on similar sand bed but, without any inclusion to determine the failure load of the footing-soil system.

TEST RESULTS AND DISCUSSION

Length of Reinforcing Elements

A series of plate loading tests, were carried out on sand bed models without inclusions and with vertical reinforcing elements placed in the soil when the test load reaches 50 % of the failure load. Eight reinforcing elements, were placed at equal spacing around the footing at a distance B from the edge of the footing. The length of the reinforcing elements inside the sand expressed as ratio (L/B) of footing diameter, were 0.5, 1.0, 2.0, 3.0 and 4.0. The load settlement curves determined from these tests are shown in dimensionless form in Figures (2), (3). From these figures, the ultimate bearing capacity of each test, was assessed unambiguously, and the bearing capacity ratio was drawn against the ratio L/B, Figure (4). From these figures, it can be seen that : i) The presence of reinforcing elements had improved the bearing capacity of the footing by up to 25 % in case of dense sand; (D_r = 90 %) and up to 13 % in case of medium sand; (D_r = 38 %). ii) As the relative length of reinforcing elements (L/B) increases, the footing load capacity increases, up to L/B equal twice the footing diameter. Beyond this ratio (L/B > 2) , there is inappreciable effect of L/B on the bearing capacity of the footing-soil system. Generally, to get the most beneficence of soil reinforcement, the length of the reinforcing elements, should be extended to a sufficient depth below the failure surface of footing-soil system. Due to soil movements underneath the footing, the developed vertical shear stress along the top portions of these elements above sliding surface will be in the opposite direction if they are compared to the shear stresses mobilized along the bottom portions of these elements below the sliding surface. Thus, reinforcing elements have effects on bearing capacity of footing if they have sufficient anchorage length. Figure (4) confirmed that there is no beneficence of increasing the penetration depth of reinforcing element beyond a limit value of L/B = 2.

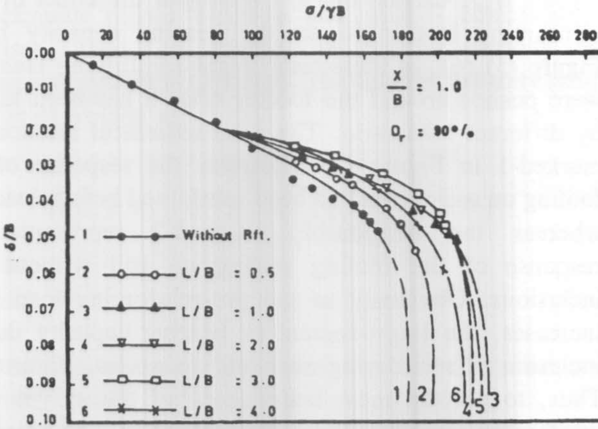

Figure 2. Load-settlement relationship with and without reinforcing elements.

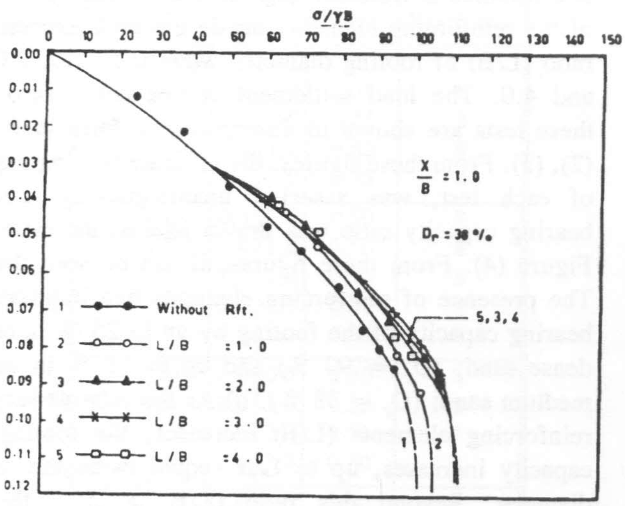

Figure 3. Load-settlement relationship with and without reinforcing elements.

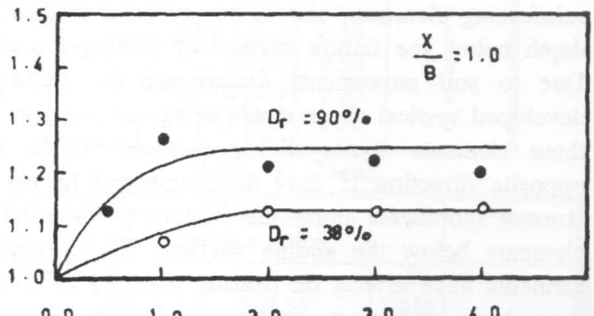

Figure 4. Effect of L/B on B.C.R.

Effect of Pre-reinforcing Load Ratio

Tests were carried out to investigate the effect of pre-reinforcing load ratio on the bearing capacity ratio; Figure (5) (6). In these tests, eight reinforcing elements were pushed around the footing after it has been loaded by different load ratio. The load-settlement relationship marked-1 in Figure (5) illustrates the response of the footing on soil which had been reinforced before loading, whereas the relationship marked-2 represents the response of the footing resting on soil without any inclusions. Obviously as the pre-reinforcing load ratio increases, the improvement in bearing capacity due to inclusion of reinforcing elements decreases, Figure (6). Thus, to get the most beneficence of the existence of reinforcing elements, these elements should be placed in soil before loading the footing. Once the footing is loaded, planes of failure commenced, and the developments of these planes are associated with the increase of the load acting on the footing. Thus, placing of reinforcing elements in soil, afterward, will decrease the subsequent tensile strains in soil, consequently, contribute in the bearing capacity of the system. Besides, it has appeared that these reinforcing elements resist lateral displacement of the soil underneath the footing and creates a sand-confinement situation. Thus, placing of reinforcing element in soil interrupt the plane of velocity discontinuities and change the directions of these velocities.

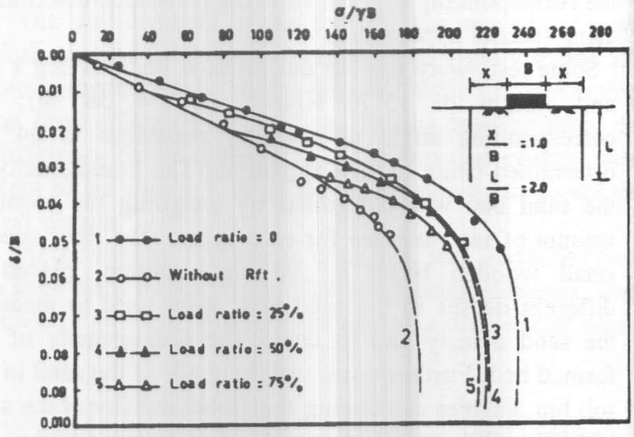

Figure 5. Load-settlement relationship with and without reinforcing elements.

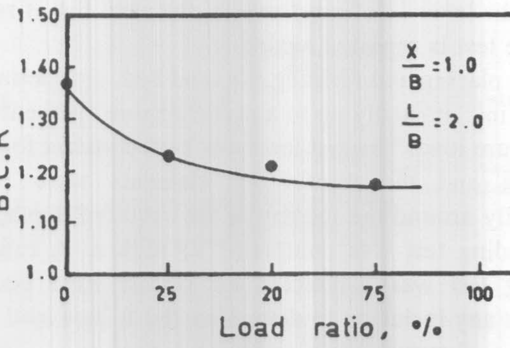

Figure 6. Effect of stress level ratio on B.C.R.

Effect of The Distance Between Reinforcing Elements and Footing

Loading tests were carried out to investigate the best location of the reinforcing elements, to get the most beneficence of their existence on the bearing capacity of footing-soil system, Figures (7) (8). As mentioned above the increase in bearing capacity of the footing, is due to the sand confinement created by the reinforcing elements and the interruption in the velocity discontinuities planes, Figure (9). Once the reinforcing elements are placed in soil, a velocity discontinuities planes are created, in addition to the pre-reinforcing planes. As the distance between soil reinforcing elements and edge of footing increases, the confined zone of soil underneath footing increases and the length of the created planes of velocity discontinuities by reinforcing elements decreases. Thus, it is expected that bearing capacity of footing soil-system decreases as x/B increases. Thus, the best location of reinforcing elements is as close to the footing as possible. But in practice, attention should be given to the effect of instillation procedure of the reinforcing elements on the footing by decreasing the soil movements as possible as it could be. The increase in bearing capacity due to soil reinforcing elements may be expressed as; Figure (10)

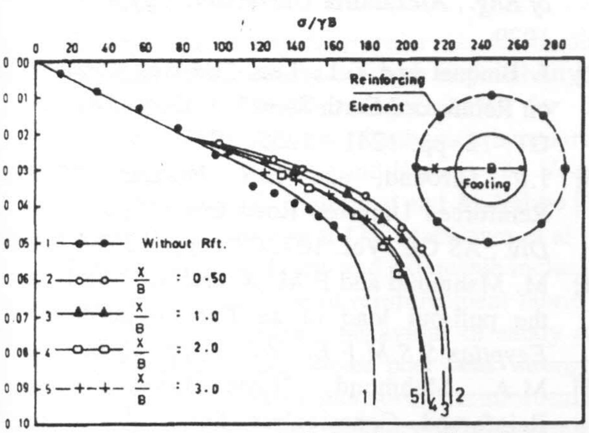

Figure 7. Load-settlement relationships with and without reinforcing elements.

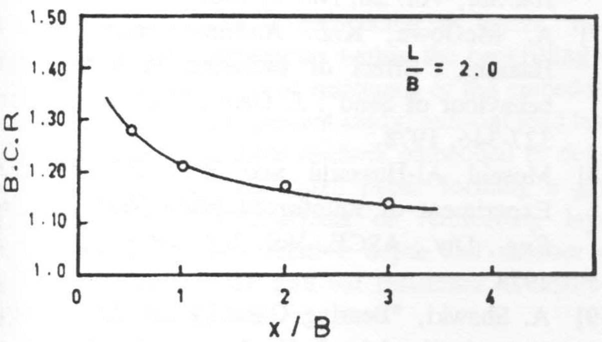

Figure 8. Effect of x/B on B.C.R.

$$(\text{B.C.R}) = 1.22 - 0.153 \log\frac{x}{B} \quad (3.0 \leq \frac{x}{B} \geq 0.5)$$

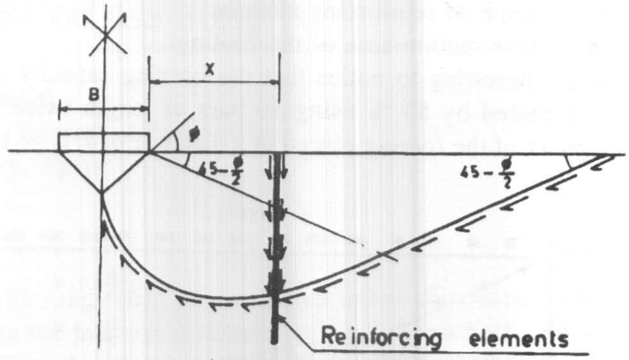

Figure 9. Surface of failure.

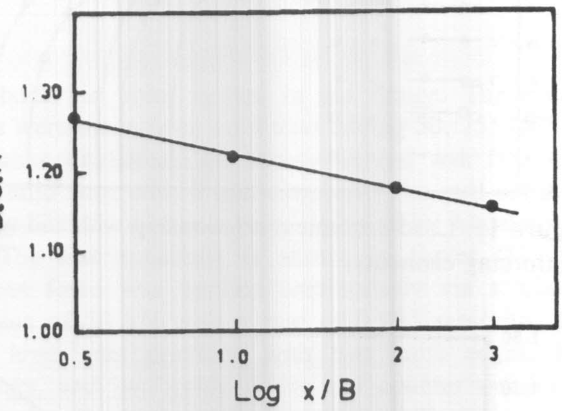

Figure 10. Effect of x/B on B.C.R.

Effect of The Number of Reinforcing Elements

Loading tests were conducted to investigate the effect of the number of reinforcing elements on the response of the footing, Figures (11 - 12). It is obvious that, as the number of reinforcing elements increases, the velocity discontinuity planes increase and sand - confinement increases. Thus, an increase in bearing capacity of footing-soil system is expected. The bearing capacity ratio may be expressed as;

$$\text{B.C.R} = 1 + 0.73\frac{A_{sur.}}{A_{c.s}}, \quad (\frac{A_{sur}}{A_{cs}} \leq 0.76)$$

in which;

$A_{sur.}$ the sum of the surface areas of reinforcing elements

$A_{sur.} = n.\ \pi dL$

where,

n number of reinforcing elements

d diameter of reinforcing element

L length of reinforcing element

$A_{c.s}$ cross section area of the footing.

It is interesting to notice that the bearing capacity can be increased by 55 % using 16 bars of length twice the diameter of the footing placed at a distance of x/B = 1.0.

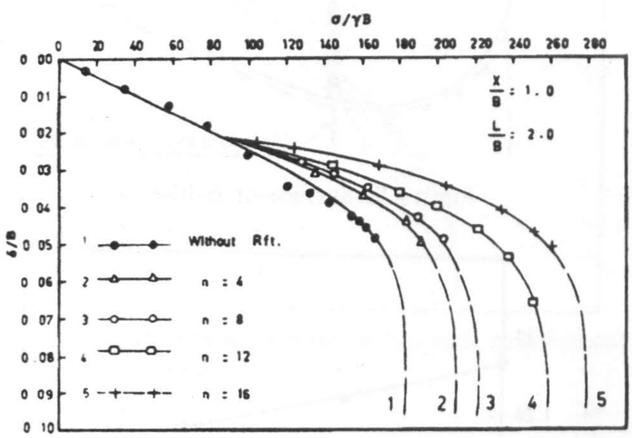

Figure 11. Load-settlement relationship with and without reinforcing elements.

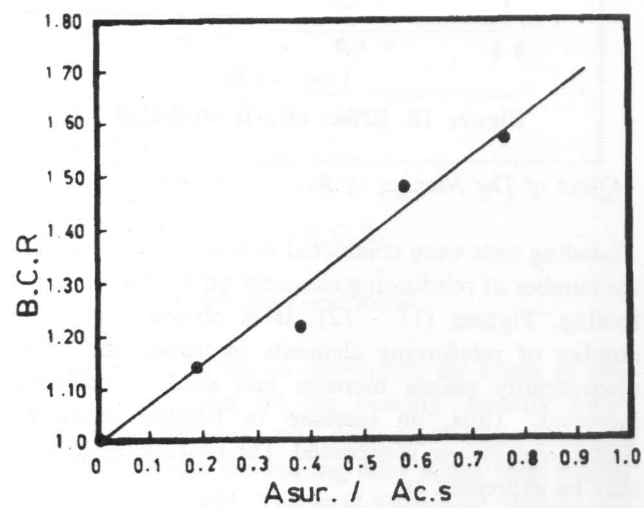

Figure 12. Effect of number of the reinforcing elements on B.C.R.

CONCLUSIONS

new adventure of utilizing soil reinforcing technique for strengthening an existing footing and consequently safeguarding a building from collapse, was introduced. Non-extensible vertical reinforcing elements are considered to be an excellent method for increasing the bearing capacity of the footing. The load-displacement behaviour of the footing is interrupted and modified significantly once the reinforcing elements are placed around the footing. The best location of reinforcing elements is as close to the footing as possible; the proper length of reinforcing elements is twice the diameter of the footing. Reinforcing elements can be pushed around the footing, for strengthening a footing-soil system, yet if the existing load reached 75 % of the failure load of the system.

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