Behavior of Strip Footings on Reinforced and Unreinforced Sand Slope

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ABSTRACT*:* The problem of the bearing capacity of strip footings on sand slope attracts the attention of many researchers. Some of the research work is devoted to improve the methods of the bearing capacity calculations, and the other for the improvement of the stability of the slope supporting the footing. To shed some lights on this problem, plate loading tests were conducted on a strip footing model of side dimension equal to 50 mm. The effects of the relative density of sand, the embedment of reinforcement, and the edge distance of the footing were studied. The study indicated that the improvement of the bearing capacity of a strip footing resting on reinforced sand slope depends upon the depth of the reinforcing layer, relative density of sand, and the edge distance of the footing. Comparisons between the achieved laboratory test results on unreinforced sand slope and the calculated values from published closed-form solutions were carried out. Also, the bearing capacity factors ($N_{\gamma q}$) of strip footings on reinforced sand slope were calculated.

INTRODUCTION

The applications of geotextile reinforcement in geotechnical engineering are widely spread nowadays. Among of these applications is the use of reinforcement to improve the bearing capacity of foundations. This application has attracted the attention of many researchers such as Binquet and lee (1975), Akinmusuru and Akinbolade (1981), Das *et al*. (1994), Consoli *et al*. (2002), Bathurst *et al*. (2003), and Abdrabbo *et al*. (2004). When a footing is constructed on or near a slope, the bearing capacity of the footing may be significantly reduced compared with the same footing resting on horizontal ground surface. The reduction depends on the location of the footing with respect to the slope, the slope angle, and the properties of the supporting soil. One of the possible methods to improve the bearing capacity of the footing near a slope is to reinforce the supporting soil with geosynthetics. Lee and Manjunath (2000) conducted series of numerical and model tests to evaluate the bearing capacity of a strip footing resting on reinforced sand slopes. The study emphasized on the effects of geogrid reinforcements and its location on the ultimate bearing capacity and settlement characteristics of strip footings.

LABORATORY MODEL

The soil bin which contains the sand and the footing model has a parallelogram shape of inside dimensions 2.0 m by 0.6 m in plan and 0.62 m in height. One long side wall of the soil bin was made from transparent glass to enable observing side view of the footing models during testing. The other walls of the soil bin were made from steel plates. To minimize side friction along the walls, plain Mylar sheets were used as liner for these walls. A strip model footing was made from a steel plate and provided with notch at the center of the top surface, to accommodate a bearing ball. The footing has a length of 580 mm, width (B) of 50 mm, and 15 mm in thickness.

A non-woven geotextile reinforcing material was used in this study. The geotextile is 3.5 mm thickness under 2 kN/m² (ASTM D-5199), the fabric weight 350g/m² (ASTM D-5261), the permeability 0.25 cm/s (ASTM D-4491), and the transmissivity 200 L/M/H under pressure of 2 kN/m² (ASTM D-4716). The sand was medium/ coarse particles. The effective diameter of sand is 0.14 mm whereas the uniformity coefficient 4.55. The specific gravity of sand particles is 2.64, the minimum dry unit weight 16.70 kN/m^3 (ASTM D-4254), and the maximum dry unit weight 18.74 kN/m^3 (ASTM D-4253). The optimum moisture content is 10% (ASTM D-698). The sand was formed inside the bin at different relative densities by pouring designed weight of sand into a certain volume of the bin. The footing was placed on the top surface of the formed soil in a way that the length of the footing is running the full width of the tank. Load was applied incrementally using the loading machine via calibrated proving ring. Each load increment was kept constant up to the rate of footing settlement becomes less than or equal to 0.002 mm/minute for three consecutive readings. The footing settlements were measured using two dial gauges of accuracy 0.01 mm. After completion of each test, the soil was carefully removed from the bin and the geotextile was visually inspected for any tear. It is important to note that, the width and depth of soil bin are greater than six times of the footing width so the bin boundary effects on the test results were considered insignificant. For the details of sand formation and loading process, refer to Omer (2006).

RESUTS AND DISCUSSION

Tests were performed on footing model with various reinforcement embedment depth to footing width ratios (d/B). For each (d/B) ratio, the edge distance of the footing (X/B) was 0, 1, and 2. The sand slope was kept constant at (2H to 1V) during all tests. Typical load-settlement relationships are presented in figure (1). Reference test was carried out at the same conditions of the footing and sand slope but without reinforcement. The ultimate bearing capacity of the footing is defined as the stress while the settlement of the footing proceeds unlimitedly. In case where load-settlement relationship exhibits a peak value of stress, the ultimate bearing capacity becomes well defined and equal to the peak value. Bearing capacity ratio (BCR) was calculated as the ratio between the ultimate bearing capacity of the strip footing on reinforced soil and the ultimate bearing capacity of the same footing on unreinforced soil. The footing displacement at the ultimate/peak load (S_F) is used through the presentation of the test results.

The variations of (BCR) and (S_F/B) against (d/B) are shown in figures (2-a) and (2-b) respectively. The figures indicated that the inclusion of geotextile reinforcement improves the performance of the strip footing in a way that the bearing capacity of the footing is increased and the settlement is reduced. There is an embedment depth of the reinforcing layer at which the (BCR) gets its peak value. This depth is called optimum embedment depth, which depends upon the edge distance of footing (X/B). The optimum depth ratio is equal to 0.5 in case of (X/B) is less than or equal to 1 and equal to 1.0 in case of (X/B) = 2, figure (2-a). Figure (2-b) indicates that (S_F/B) reached the minimum value at the optimum depth of reinforcement. These findings are highly consistent qualitatively with the model test results obtained by Selvadurai and Gnanendran (1989). The behavior of reinforced slope can be explained by the "deep footing effect" as suggested by Huang *et al*. (1994). The soil mass enclosed by reinforcing layer and footing-soil interface behaves as a fictitious rigid footing and transfers a major part of the footing load into deep zone, provided that there is no lateral bulging. The friction stresses developed at the footing-soil interface and along the reinforcing layer produce lateral confinement of the reinforced zone. The effect of this confinement on the stability of the sand slope decreased as the reinforcing layer goes deeper and consequently the bearing capacity of the footing decreased due to anticipated bulging of soil towards the side slope. At the same time, the load causing instability of the sand slope increased as the superimposed load at ground surface transferred deeper into the soil. These two factors are in contradictory, so there is an optimum depth of reinforcement at which the fictitious footing was formed without lateral bulging. The optimum depth of reinforcement is about 0.5 in case of (X/B) = 1, and about 1.0 in case of (X/B) = 2. At larger depths of embedment than the optimum depth, the contribution to the load-transfer mechanism caused by the presence of the reinforcement is reduced significantly.

In order to investigate the effect of the embedment ratio (d/B) on the (BCR) at different relative density of sand, figure (3) was developed. The figure illustrates that the optimum depth ratio varies from 0.25 to 0.50 in case of (X/B) = 0.0 and for all relative densities (Dr = 60%, 70%, and 85%). The optimum depth ratio varies from 0.50 to 0.80 in case of (X/B) =1.0, and varies from 0.50 to 1.00 in case of X/B =2.0. It can be concluded that the optimum depth ratio is not appreciable affected by (Dr) within the accuracy of test results. These results are in agreement qualitatively with Yoo (2001). Figures (2) and (3) demonstrated that the optimum depth ratio of the reinforcing layer depends upon the edge distance (X/B). At (X/B) = 0, the failure of footing soil system is dominated by the slope instability, but when (X/B) becomes

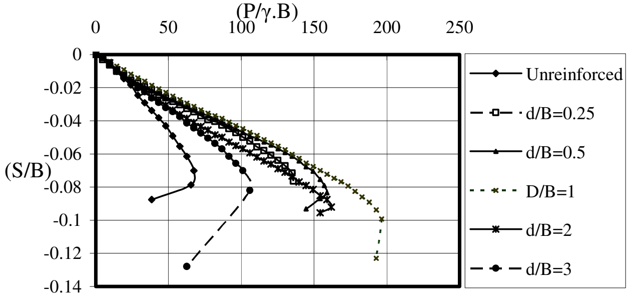

FIG. 1. Normalized stress (P/γ.B) versus (S/B) at X/B = 1.00 and Dr = 85%

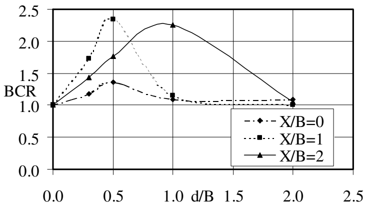

FIG. 2-a. BCR versus d/B, Dr=70%

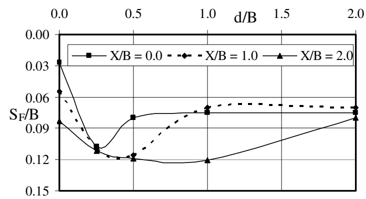

FIG. 2-b. S_F/B versus d/B, Dr=70%

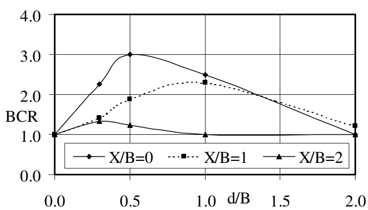

FIG. 3-a. BCR versus d/B, Dr = 60%

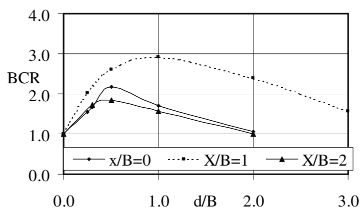

FIG. 3-b. BCR versus d/B, Dr=85%

larger than 1.0, the failure is dominated by the shear stresses developed on shear planes performed in soil beneath the footing. At (X/B) = 0, the optimum depth ratio of reinforcement is 0.5, while at (X/B) >0, the optimum depth ratio of reinforcement becomes greater than 0.5 and approaches to unity.

Series of tests were performed at different (X/B) ratios. During each series of tests, the (d/B) ratio was kept constant at a specified value. Figures (4-a), and (4-b) showed that for unreinforced sand slope, the bearing capacity of strip footing increases as (X/B) increased. In case of reinforced sand slope, the bearing capacity of strip footing depends upon two main factors; the depth of the fictitious rigid footing and the stability of side slope. The first factor depends on the depth of reinforcing layer while the other factor depends on the relative density of sand. So it can be concluded that two inter-related factors, depth ratio (d/B) and relative density of sand (Dr), are affecting the response of strip footing on reinforced sand slope. Furthermore figures (4-a) and (4-b) showed that at any given edge distance, the ultimate bearing capacity of a strip footing near a reinforced slope is considerably higher than that of the same footing near unreinforced slope, this behavior reflects the beneficial effect of reinforcement in improving the bearing capacity of strip footing near a slope. The effect is obvious in case of soil with low relative density. This can be attributed to the modulus of deformation of soil relative to the modulus of deformation of the reinforcing layer. For higher values of (Dr), the modulus of deformation of soil is approaching that of reinforcing material so the existence of reinforcement may not be effective.

Figure (5) illustrates the ultimate bearing capacity (qu) of a strip footing near unreinforced sand slope versus (X/B) values at different relative densities of soil. It can be concluded that the bearing capacity increased as the edge distance of the footing increased, in case of (Dr) > 70%. For soil having small relative density, there is unappreciable effect of the edge distance of the footing on the bearing capacity, for (X/B) > 1. This can be attributed to the failure patterns underneath the footing. In case of soil with (Dr) ≤ 70%, local shear failure underneath the footing with a limited wedge extent is anticipated. In case of soil with (Dr) > 70%, general shear failure of footing-soil system is expected, and the soil wedges may extend to intersect with side slope

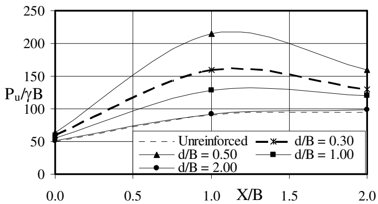

FIG. 4-a. (Pu/B.γ) versus(X/B), Dr = 60%

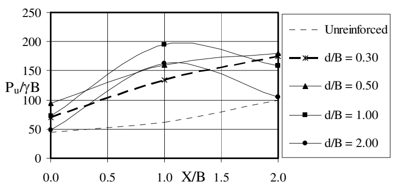

FIG. 4-b. (Pu/B.γ) versus(X/B), Dr = 85%

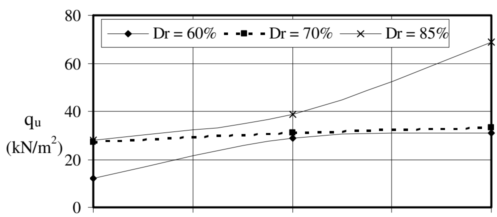

FIG. 5. Ultimate bearing capacity (qu) versus (X/B) for unreinforced soil

COMPARISON BETWEEN EXPERIMENTAL AND THEORETICAL BEARING CAPACITY VALUES

Four methods were implemented to asses the experimental ultimate bearing capacity of footing-soil system from the achieved load-settlement relationships. These methods are; (a) two tangent lines were drawn from the initial and end points of the load-settlement relationship and the point of intersection of these two tangents was projected to the X-axis to obtain the ultimate bearing capacity, (b) the ultimate load for each test was determined at (S/B) = 5%, (c) The ultimate load is defined as the maximum load, while the settlement of the footing proceeds unlimitedly, in case where a peak value of load is obvious, the ultimate load becomes well defined and equal to the peak value, and (d) the ultimate load for each test was considered as the load corresponding to (S/B) = 2.5%. The theoretical bearing capacity was calculated using Meyerhof (1957), Gemperline (1988), and Graham *et al* (1988). Figures (6) to (8) indicated that Meyerhof equation underestimates the bearing capacity of a strip footing resting near a sand slope. The underestimation depends upon the method implemented for interpreting the ultimate bearing capacity, Omer (2006). The underestimation factor varies between 0.32 and 0.60. Gemperline equation agrees with the measured bearing capacity obtained, by method (a), while, underestimated the value obtained by methods (b) and (c), and overestimate the value obtained by method (d) by a factor 1.142. Graham *et al* equation agrees well with the predicted values by methods (a) and (d), and underestimated the value obtained by methods (b) and (c). If we considered the average of the obtained values of the ultimate bearing capacity, it can be concluded that Meyerhof equation underestimate the bearing capacity value by a factor 0.4, while Gemperline by a factor 0.87 and Graham *et al* by a factor 0.81. Gemperline and Graham *et al* equations give, nearly, the same results (Omer 2006). In order to calculate the bearing capacity of a strip footing on reinforced sand slope, Meyerhof (1957) equation was suggested, but with different bearing capacity factor ($N\gamma q$), figure (9). These factor are valid only for strip footings resting on top surface of sand with (Dr) = 60%, and slope of 2:1.The factor ($N\gamma q$) depends upon (X/B) ratio, (d/B), and Dr (Omer 2006). These values should be used with caution due to scale effects.

SCALE EFFECTS

The scale effect phenomenon of the footing was explored by many authors; De Beer 1963, Tatsuoka *et al.* 1994, Kusakabe 1995, and Cerato & Lutenegger 2007. Cerato and Lutenegger (2007) showed that the interpretation of the bearing capacity factor ($N\gamma$) from model footings is dependent on the footing width (B). Tatsuoka *et al.* (1994) reported that the scale effects are resulted from two factors; the mean stress level beneath the footing and the particle size. Kusakabe (1995) stated that the particle size effect ($B/d_{50\%}$) becomes insignificant on the obtained results, when ($B/d_{50\%}$) becomes greater than 50 – 100. In our study, the value of ($B/d_{50\%}$) is about 100. Consequently the effect of the second factor on the test results is avoided. The effect of the first factor is difficult to be avoided unless a modification of the bearing capacity factor is carried out, Shiraishi (1990).

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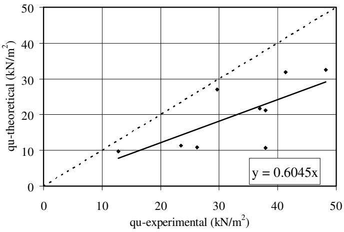

FIG. 6. Experimental and theoretical results (Meyerhof, 1957), method (d)

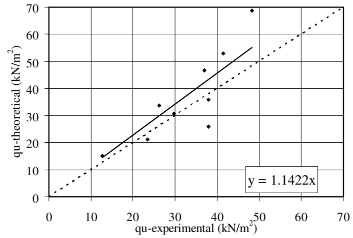

FIG. 7. Experimental and theoretical results (Gemperline, 1988), method (d)

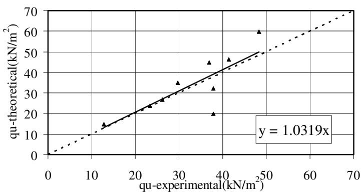

FIG. 8. Experimental and theoretical results (Graham *et al*, 1988), method (d)

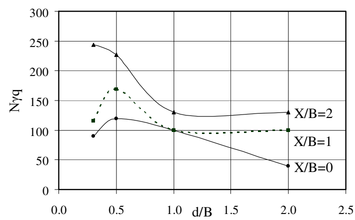

FIG. 9. Values of $N_{\gamma q}$ versus d/B, single reinforcement, and Dr=60%

CONCLUSIONS

1. Geotextile reinforcement is effective in the improvement of bearing capacity of a strip footing resting near a sand slope. The effect of reinforcement depends on the geotextile depth, relative density of sand, and location of the footing with respect to the slope face.
2. The optimum depth ratio of geotextile reinforcement varies from 0.25 to 0.50 in case of (X/B) =0.0, from 0.50 to 0.80 in case of (X/B) =1.0, and from 0.50 to 1.00 in case of (X/B) =2.0. The effect of reinforcement on the bearing capacity of sand slope is more pronounced in soil with low relative density.
3. For unreinforced sand, there is no effect of sand slope having Dr ≤ 70% on the footing performance in case of X/B ≥ 1.0 while the sand slope with Dr = 80% affects the footing behavior.
4. Meyerhof equation underestimated the bearing capacity of a strip footing on sand slope by a factor of 0.4, while Gemperline and Graham et al by a factor of 0.87 and 0.81 respectively.

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