Performance of Skirted Strip Footing Subjected to Eccentric Inclined Load

Article *in* Electronic Journal of Geotechnical Engineering · January 2008

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ABSTRACT

Skirted foundations, in which vertical or inclined wall surrounds one or more sides of the soil mass beneath the footing, is one of the recognized bearing capacity improvement techniques. Construction of vertical skirt at the base of the footing, confining the underlying soil, generates a soil resistance on skirt side that helps the footing to resist sliding. Laboratory work and numerical analysis were performed to study the behavior of one sided skirted strip footing subjected to eccentric and inclined load. Various load inclination angles, load eccentricities and skirt lengths were investigated. Bearing capacity values for all cases were compared, and favourable design conditions were suggested.

KEYWORDS: finite element method; skirted footing, model strip footing tests, bearing capacity.

INTRODUCTION

Footings of retaining walls, abutments, industrial machines, and portal framed buildings are not only subjected to vertical or inclined loads but also to moments. Moments on the foundation base are mainly caused by horizontal forces acting on the structure. Horizontal forces are the resultant of earth pressure, wind pressure, seismic force, and water hydrostatic pressure etc. These forces and moments can be replaced by eccentric inclined load on the footing. The general objective of this research is to study the behavior of one sided skirted strip footing under the effect of eccentric inclined loads. The research comprises of an experimental investigation and a numerical analysis. The experimental work was directed to study the effect of variation of load eccentricity, load inclination angle, skirt length, and skirt inclination angle. Numerical analysis was carried out using the finite element software PLAXIS, Version 7.1. The validity and efficiency of the numerical analysis was evaluated by comparing the load-settlement responses from the model footing test data and the finite element results.

Recently, using a ring beam or a skirt as soil improvement technique has been investigated by many researchers. They used the ring beam under circular foundation (Mahiyar and Patel 2000, Martin 2001, EL Sawwaf and Nazer 2005). They have noticed a significant improvement in the footing response due to the ring beam resistance to lateral displacement of soil underneath the footing. Boushehrian and Hataf (2003), Laman and Yildiz (2003) experimentally investigated the ultimate bearing capacity of ring foundations supported by a sand bed with and without geogrid reinforcement. The results proved that the ultimate bearing capacity values can be improved up to three times that of the unreinforced case.

Rao and Narhari (1979) developed a skirted plug foundation and indicated that the provision of skirting to the soil plug is generally beneficial and can be applied when the settlement is restricted for a given load. Ranjan and Rao (1985) improved the soil by using granular piles surrounded with skirts. They found out that the granular skirted pile foundations have a lot of potentiality for structures which are sensitive to settlement and are subjected to heavy loads. Ortiz (2001) inserted a discontinuous vertical skirt dowels around existing foundation. A marked increase 20 % in the bearing capacity and a reduction of settlement were observed. Al-Aghbari and Zein (2004, 2006) carried out tests on strip and circular footing models resting on sand. Their results showed that the use of structural skirts improved the bearing capacity by a factor up to three.

Mahiyar and Patel (2000) have utilized the software package ANSYS to study the effect of using a skirt to prevent footing tilting due to eccentric loading. They provided a downward vertical projection to the footing at the edge near the eccentric load. They indicated that for a given value of eccentricity, the tilt can be reduced to almost zero by providing a vertical skirt. Bransby and Randolph (1999) used the FEM to study the effect of vertical skirt under strip and circular foundation. Results indicated that the use of skirt with circular foundation gave better improvement than that obtained from strip foundation. Gourvenec (2002, 2003) applied two and three dimensional finite element analysis to assess the behavior of strip and circular skirted foundations subjected to combined vertical, moment, and horizontal loading. The skirt enhanced vertical, horizontal, and moment load capacity compared to flat foundations.

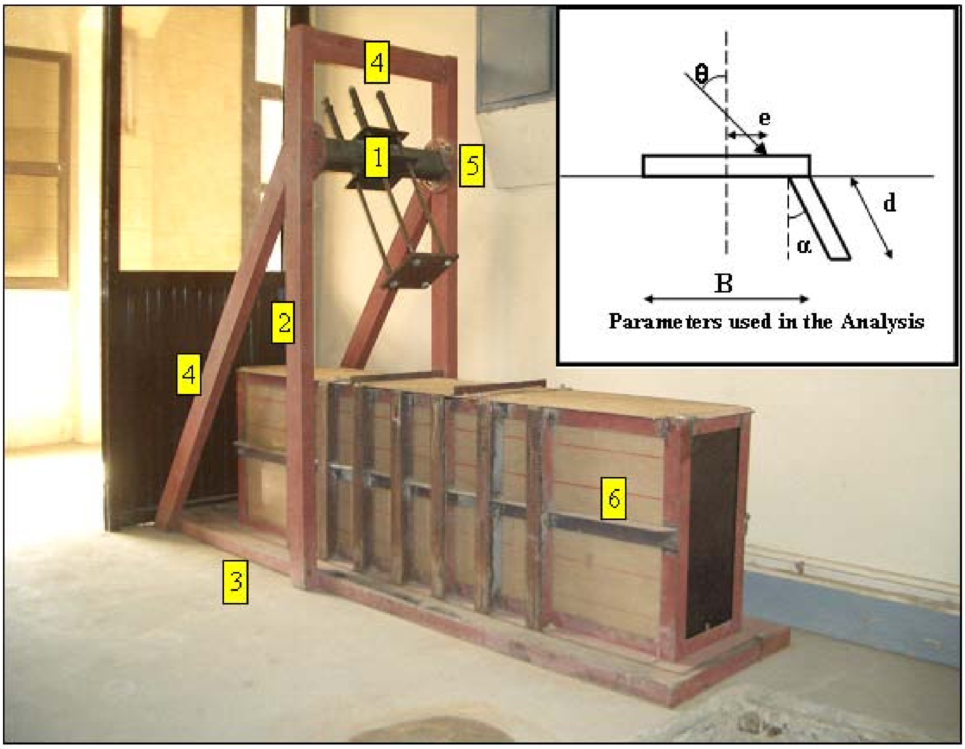
Yun and Bransby (2003) carried out a series of centrifuge model tests to investigate the response of skirted foundation on loose sand under combined vertical, horizontal, and flexural loading. The tests showed that the horizontal capacity of the skirted foundation was increased to about 3~4 times that of plane foundation. They also suggested that the foundation failure mechanism changed from sliding to a rotational mode. Appolonia et al. (1968) studied the effect of changing the angle of the skirt connected with the footing on the sand compressibility. They observed that the sand compressibility decreased rapidly as the angle of skirt increased from zero to 30˚ with the vertical, and attained nearly a constant value for angles between 30̊ and 45˚. Giri (1994) constructed a laboratory model for skirted footing by assembling four plates around the periphery of footing subjected to vibrated eccentric load. Results indicated that increasing the inclination angle of the skirt has a remarkable increase in resonance frequency and a decrease in amplitude.

Most of the previous studies concentrated on using a structural skirts or ring beam to confine the soil under footings subjected to concentric or eccentric load. This research was conducted to study experimentally and the analytically the performance of the skirted strip footing subjected to eccentric-inclined load which has not been covered in most of the previous research.

EXPERIMENTAL WORK

Test Apparatus and Material Used

The model loading tests of the skirted strip footing consists of: test tank, loading system, footing model, and the measuring devices. The test tank is a stiffened framed tank having inner dimensions of 200cm in length, 30cm in width, and 60cm in depth. The front and the back long sides of the tank were made of two transparent perspex plates of 10mm thick, which were fixed by rigid frames and restrained by steel stiffeners (Fig.1). The footing model used is 200 mm rigid steel plate with a rough base. Four screw holes at equal spacing along the edge of the footing were made to connect the skirt to the footing by means of steel bolts. A loading frame and a hydraulic jack were used to apply the load. The load was transmitted to the footing through 50-KN proving ring arranged between a connecting rigid bars and the hydraulic jack. Three sensitive dial gauges were employed to measure the footing displacement. Two of which measure the vertical displacements and the third measures the horizontal displacement.



1. Horizontal reaction beam 2. Two columns 3. Base
4. Bracing 5. Four flanges 6. Testing tank
Figure 1: Loading Frame

Oven dried poorly graded medium sand was used for this study. The sand has a coefficient of uniformity of 3.33 and gradation coefficient of 1.04. The specific gravity was found to be 2.63. Maximum and minimum values of the dry unit weight are 1.89 and 1.59 gm/cm^3, respectively. The relative density of the sand used in the model tests was 60 % which has a friction angle of 40°, determined by a direct shear test.

Test Procedure

A predetermined weight of dry sand, needed to satisfy the target relative density, was poured and compacted inside the tank in layers, 100 mm thick. The compaction was accomplished by tamping on the surface of the sand layers. The compaction was determined by using the depth marking on the sides of the transparent Perspex tank as a guide. The accuracy of sand density placement inside the tank is checked by conducting three preliminary density tests. The variation of sand relative density was found to be 60% ±3%. A cell pressure was installed on the skirt side and connected to the data logger. The skirt and the guide beam were bolted together using four screw bolts, then, the guide beam was fixed to the top angles of the tank sides using bolts and nuts. This installation keeps the skirt in place during the sand filling around it. After completing the sand filling, the guide beam was removed and the model strip footing was fixed to the skirt. The load was slowly applied to the footing, at the required eccentricity and load inclination angle, using the hydraulic jack. The load was applied to the footing in small increments and the corresponding deformations were measured by the dial gauges.

Testing Program

The objective of the present research is to study the behavior of skirted strip footing subjected to eccentric inclined load. The study was performed to evaluate the effectiveness of providing a single skirt to the strip footing at the edge near to the load. The experimental work of skirted footing model implemented on sand is presented, discussed, and a comparison between footing model tests with and without skirt was conducted. Load eccentricity, load inclination angle, skirt length, and skirt inclination angle are the main variables in these tests. A series of 60-experimental model skirted strip footing tests were carried out for eccentrically inclined loaded footing with and without skirt and supported by sand compacted at a relative density of 60%. Load eccentricity, e, varied from zero to 35% of footing width, B, (i.e. e=0.0, 0.05B, 0.15B, 0.25B,and 0.35B), executed with three load inclination angles, θ, of 10°,20°,and 30° with the vertical. The skirt length, d, varied from zero to the footing width (i.e. d = 0.0, 0.25B, 0.50B, and B). In addition, 12 tests were carried out on skirted strip footing with inclined skirt angles, α, of 10°, 20°, 30°, and 45° with the vertical.

Footing without Skirt

For a basic case of comparison, the first set of tests was done for strip footing without skirt and subjected to centric load at different load inclinations. The load was applied at inclination angles of 10°, 20°, and 30° with the vertical. As expected, the ultimate bearing capacity decreased with the increase of load inclination angle (θ).The amount of decrease in the bearing capacity of inclined loaded strip footing on top of compacted sand compared to that vertically loaded may be expressed in terms of bearing capacity inclination factor (i). A good agreement was obtained between the present test results and other researchers for the bearing capacity inclination factors.

Skirted Footing Behavior

Some of the 60 experimental model skirted strip footing test results for load-settlement, load-horizontal displacement, and load-rotation relationships are shown in Figure 2, 3, 4 and 5. The footing without skirt is shown on their corresponding figures and used as the basic case of comparison for the same loading conditions. All test results indicated the same trend as the ultimate bearing capacity increases with the increase of skirt length. The failure load can be found at the point of rapid progressive settlement or when the footing starts to slide horizontally. Results indicated that the footing tilt increases with the progress of loading. Therefore the horizontal component of the inclined load increases with the increase of footing tilt. The horizontal component of the load is the main force of sliding, which is resisted by the shear developed between the footing base and soil underneath. Embedment a single skirt under the footing provided a resistance to sliding against lateral loads. The effect of load inclination angle on the load–settlement behavior of skirted footing is more pronounced for skirt length d/B=0.25. This due to the horizontal component of the inclined load forces the footing to sliding failure. With increasing the skirt length to d/B = 0.50, sliding failure was prevented. This due to the resultant of the horizontal soil reaction on the skirt side is a function of the skirt length and horizontal displacement.

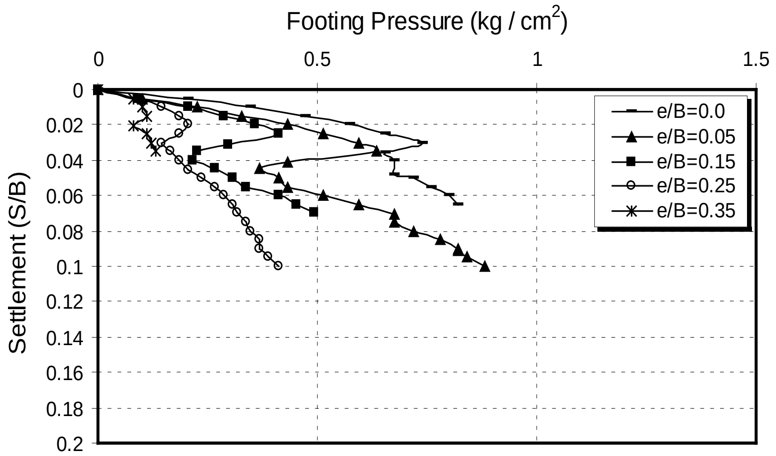


Figure 2: Load-settlement relationship for footing subjected to eccentric load (θ=20º and d/B=0.25).

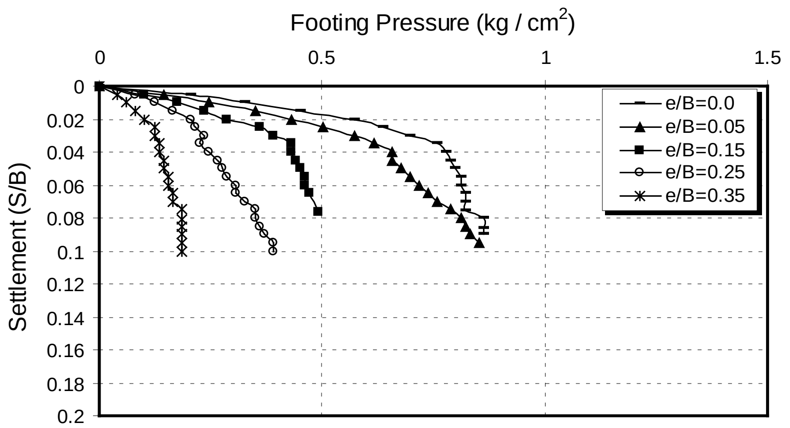


Figure 3: Load-settlement relationship for footing subjected to eccentric load (θ=20° and d/B=0.50).

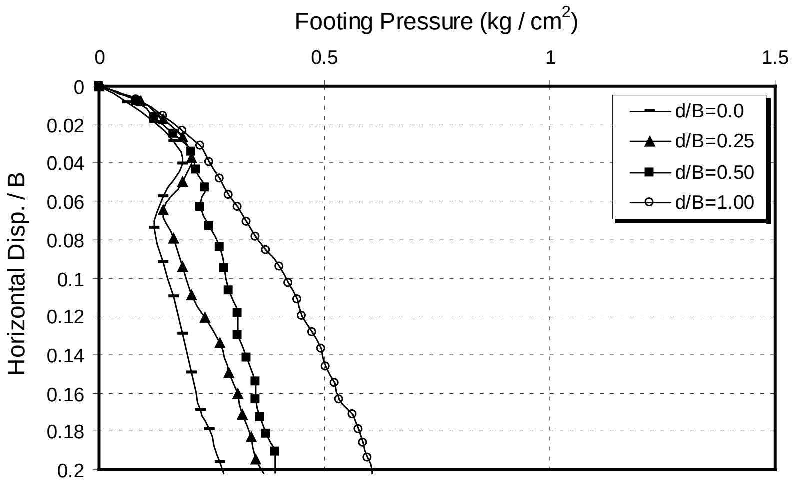


Figure 4: Load-horizontal displacement relationship for footing subjected to eccentric inclined load (θ=20º and e/B=0.25).

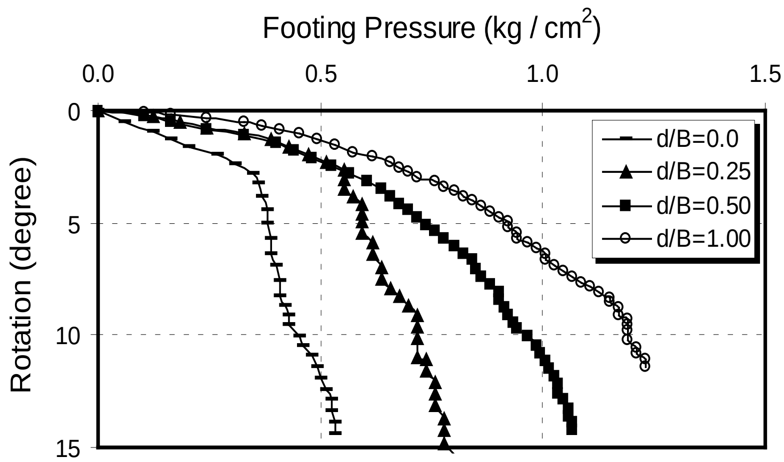


Figure 5: Load-rotation relationship for footing subjected to eccentric inclined load (θ=10 º and e/B=0.25).

The increase in the ultimate bearing capacity of skirted footing compared to footing without skirt can be best expressed in terms of non-dimensional parameter called the ultimate Bearing Capacity Ratio (BCR_u). The amount of increase in the ultimate bearing capacity ratio due to the use of skirt for different load inclination angles of 10°, 20°, and 30° is shown in Figure 6. The BCR_U is plotted against the corresponding, d/B, ratio for different values of load eccentricity, e/B. The BCR_u increases with the increase in skirt length. This is due to the increase in the horizontal soil reaction generated on the outer skirt side which improves the footing stability. Generally, the BCR_u increased with the increase in skirt length and reached its best value at skirt length of d/B = 0.50, and the rate of improvement reached about 5.50 times that of footing without skirt.

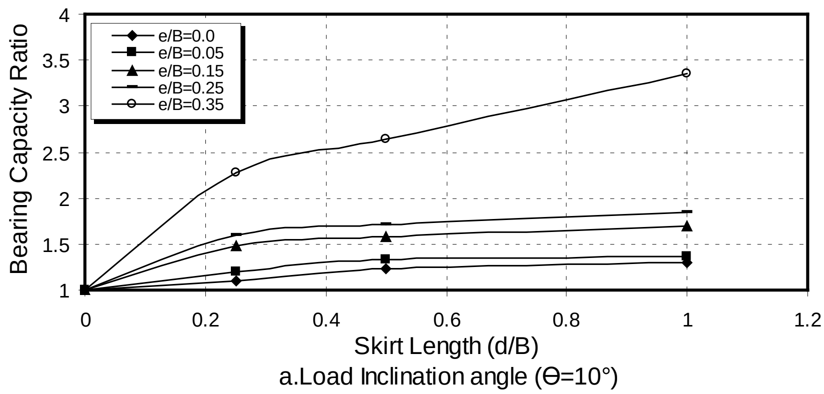


Figure 6*a*: Ultimate bearing capacity improvement ratio for different load inclination angles versus skirt length.

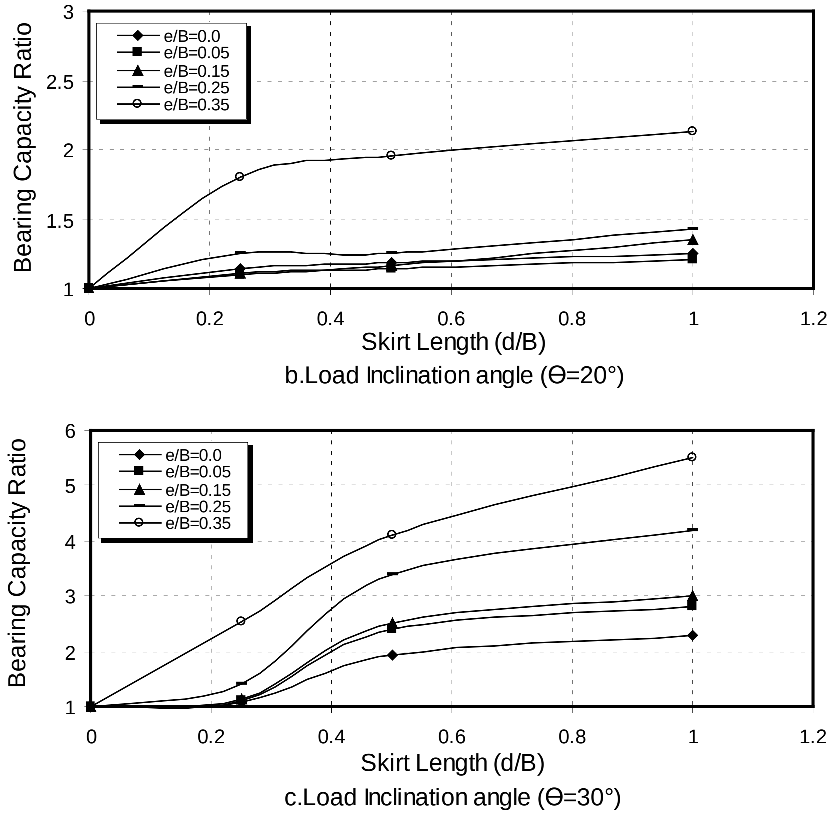


Figure 6*b, c*: Ultimate bearing capacity improvement ratio for different load inclination angles versus skirt length.

Referring to the test results, the effect of load inclination angle, θ, load eccentricity, e/B, and skirt length, d/B, on the ultimate bearing capacity, q_{ult}, can be expressed in the following empirical formula.

$$q_{ult\ (\theta,\ e/B,\ d/B)} = q_{ult}\ R\ (1 - 0.03\ \theta) + X\ (d/B)$$

Where $X = 0.30$ for $\theta < 20°$
$X = 0.10$ for $\theta \geq 20°$

$(q_u)_{\theta\ ,e/B\ ,\ d/B}$ is the ultimate bearing capacity of the skirted footing and (q_u) is the ultimate bearing capacity of the footing without skirt and subjected to vertical concentric load and its value can be calculated from any conventional bearing capacity equation. R is the eccentricity reduction factor for the ultimate bearing capacity and can be obtained from Figure7 as a function of e/B.

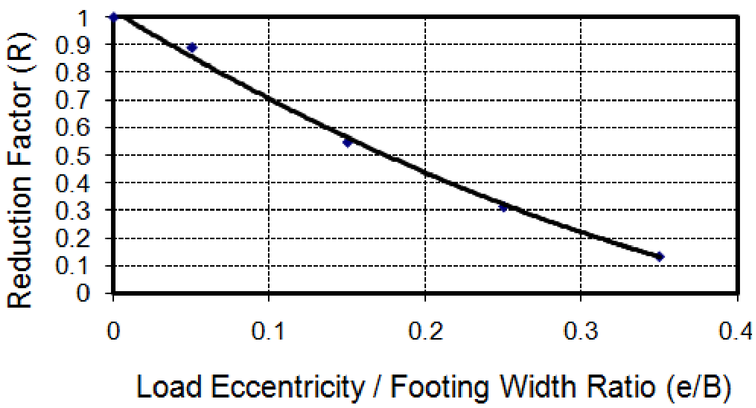


Figure 7: Load eccentricity reduction factor for ultimate bearing capacity.

Effect of Skirt Angle

This section deals with footing of inclined skirt. The inclination angle of the skirt to the vertical varied from zero to 45°. The improvement ratio in the ultimate bearing capacity of skirted footing subjected to inclined load is shown in Figure 8. Curves are plotted for different values of skirt inclination angle (α): 10°, 20°, 30°, and 45°, and at different load inclination angles (θ): 10°, 20°, and 30° with the vertical. The improvement in the ultimate bearing capacity increased with the increase of both load inclination angle and skirt inclination angle. The contact area and adhesion between the footing and the soil increased with the increase of skirt angle. The horizontal projection of the whole footing (plane + skirt) increased from B, in case of vertical skirt, to 1.7B in case of skirt inclination angle of 45° to the vertical. This means that increases in skirt inclination angle leads to high contact area between the footing and the soil which improves the footing stability.

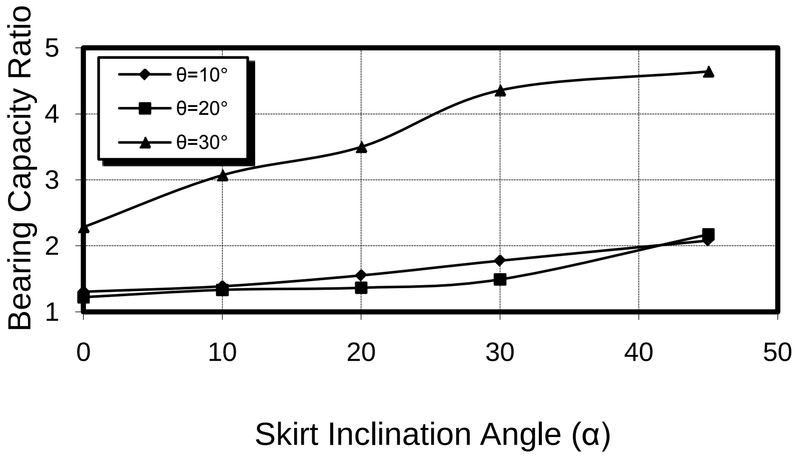


Figure 8: Ultimate bearing capacity improvement ratio for different values of load inclination angle, θ, and skirt inclination angle, α.

NUMERICAL MODEL RESULS

Numerical analysis was conducted using the finite element method (FEM) to verify the model test results and examine configurations which have not been modeled experimentally. The FEM can be particularly useful for identifying the patterns of deformations and stress distribution in the soil. Monitoring the soil behavior under applied loads is expensive so, the use of numerical analysis is useful to predicate the soil behavior throughout its life time. The FEM gets more powerful as its results verified with experimental results. The elasto–plastic finite element analysis was carried out using the commercial program PLAXIS version 7.1. All the finite element calculations were based on the mesh generation process that searches for optimized six nodded triangle elements .The boundary conditions were chosen such that the vertical boundary was constrained horizontally and the horizontal boundary at the base of the tested tank was constrained in both the horizontal and the vertical direction. In this study the sand was modeled using the hardening soil model which uses the hyperbolic model of Duncan and Chang (1970). The soil parameters of this model were derived from a series of laboratory drained triaxial compression tests. These parameters are: unit weight (γ) of 1.76 g / cm^3, angle of internal friction (ϕ) of 40°, cohesion(c) of zero kg /cm^2, failure ratio (R_f) of 0.9, degree of the dilatancy angle (ψ) of 8.0, Power for stress-level dependency of stiffness (m) of 0.60, Secant stiffness in standard drained triaxial test (E_{50}^{ref}) of 200 kg/cm^2, and Poisson's ratio of 0.30.

COMPARATIVE ANALYSES

Some experimental results for skirted footing were chosen for comparison with the results of the FEM as shown in Figure 9 and Figure10. The result shows that the FEM is capable of predicting the soil behavior to a good level of accuracy. The FEM gave higher values for the ultimate bearing capacity than that obtained from the experimental work. This difference increased with the increase of both load eccentricity and load inclination angle. However, the FEM and the experimental work had the same trend; the ultimate bearing capacity decreased with the increase in the load eccentricity and load inclination angle. This is due to the horizontal component of the inclined load which forces the footing to slide, and consequently reduces the ultimate bearing capacity as demonstrated by the displacement field in Figure 11. Inserting a skirt under the footing edge reduces the lateral movement of soil as shown in Figure 12. Generally, the deformations mostly occurred on the loaded side of the footing, and the mesh deformation is less at the other side of the footing as shown in Figure 13.

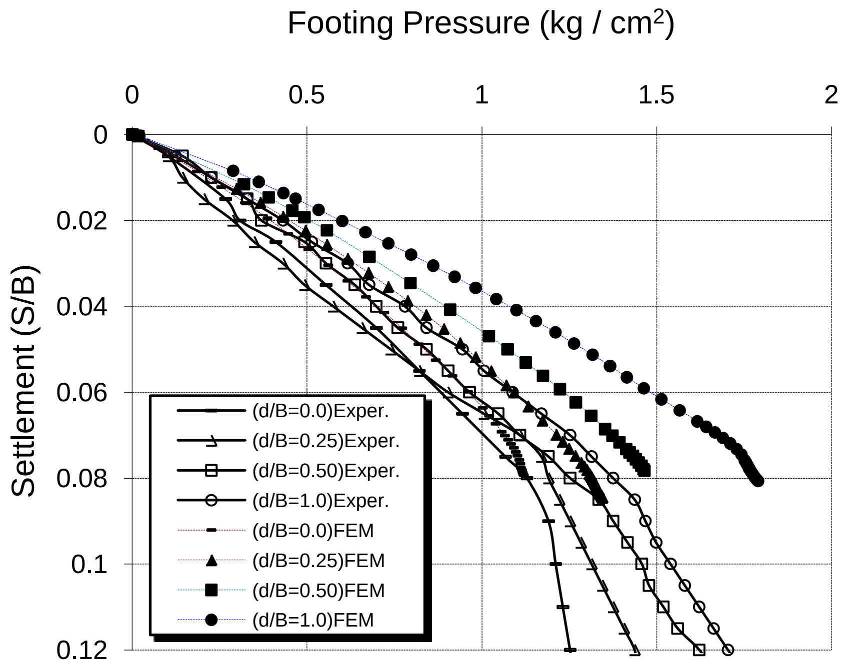


Figure 9: Comparison between experimental work and FEM for load-settlement curves of skirted footing subjected to vertical eccentric load (e/B=0.15).

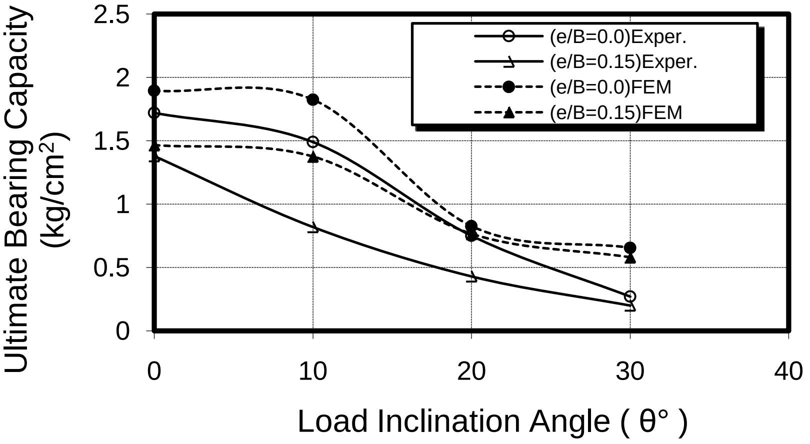


Figure 10: Comparison between experimental work and FEM for ultimate bearing capacity of skirted footing, d/B=0.50,subjected to inclined eccentric load.

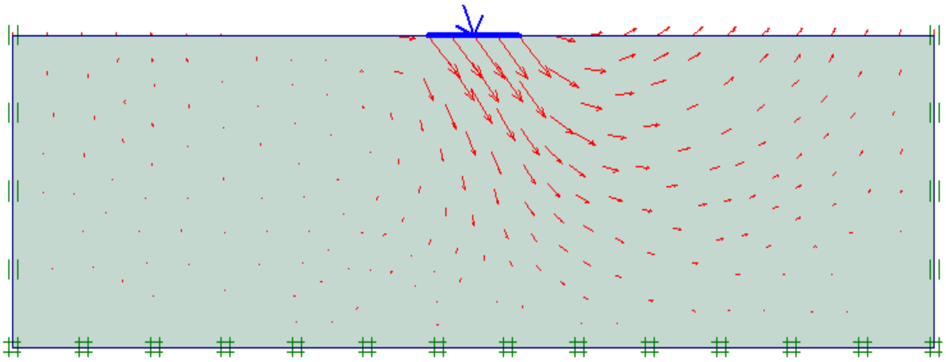


Figure 11: Displacement field for footing without skirt subjected to inclined centric load (θ=20°, e/B =0.0 & d/B =0.00).

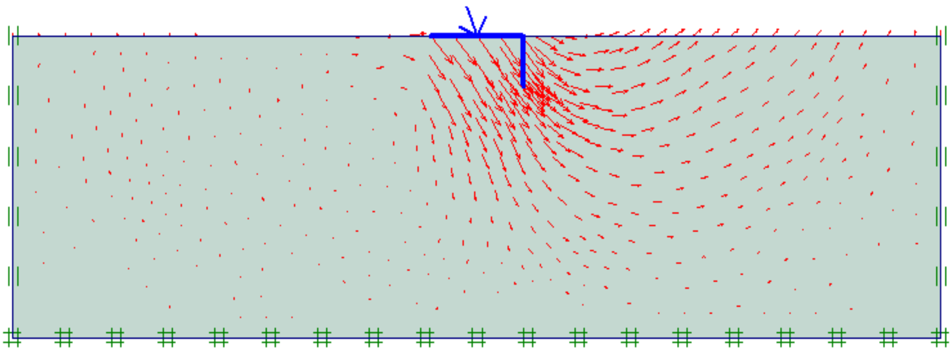


Figure 12: Displacement field for skirted footing subjected to inclined centric load.

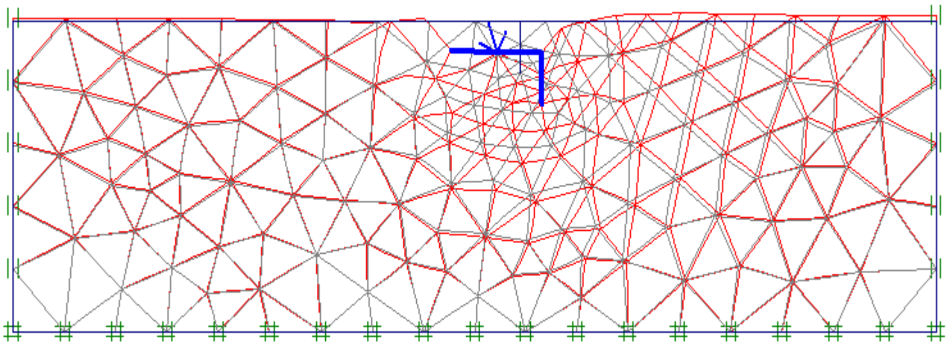


Figure 13: Deformed finite element mesh of skirted footing subjected to inclined centric load (θ=20°, e/B =0.0 & d/B =0.50).

The horizontal soil reaction on the outer side of the skirt was measured during the experimental model tests by using two pressure cells equipped with electric resistance strain gauges. The values of the horizontal soil reaction, measured during the experimental work at the failure load, were compared with the results obtained from the FEM analysis. The comparison is shown in Figure 14 and 15. It is clear that a complete agreement between the results of the experimental work and those of the FEM is difficult to achieve because of the complex interaction between the various components of the skirted footing. Also, the boundary conditions and the geometry of the mesh have a significant effect on the finite element analysis. However, the comparison between the values obtained by using the finite element method, and experimental results demonstrates the capability of the computer program PLAXIS to predict the behavior of the horizontal soil reaction on the skirt side. Results of the FEM values were always higher than that of the experimental measurements. The difference is smaller at lower load eccentricity and e/B. At higher load eccentricity and e/B of 0.35, the predicted value is much higher than the experimental value. That means the FEM analysis gives more conservative values.

Generally, the ultimate bearing capacity was reduced by increasing load eccentricity, e/B, and load inclination angle, α. The failure load is attuned with the lateral movement of the skirted footing subjected to eccentricity or inclined load. The horizontal soil reaction on the outer side of the skirt must be a function of the lateral movement of the footing. The horizontal soil reaction developed on the skirt side creates more resistance to footing sliding. Moreover, when the skirted footing is subjected to eccentric or inclined load, the footing is forced to rotate in the same direction of the load. This means that the skirted footing moves laterally towards the soil at the top of the skirt more than the lower part. Also, the results indicate that the horizontal soil reaction increases with the increase in the skirt length. This is because it increases the volume of the displaced soil, which accordingly increases the soil pressure.

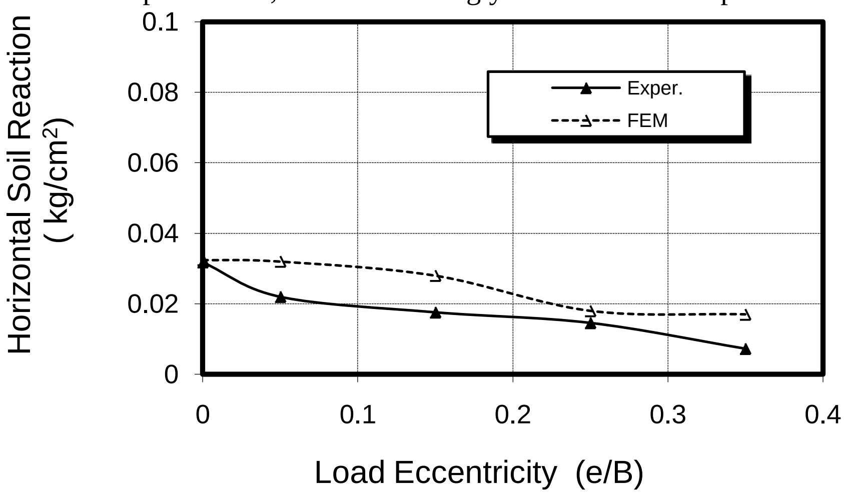


Figure 14: Variation of horizontal soil reaction at the bottom of the skirt (d/B=0.50& θ=10º).

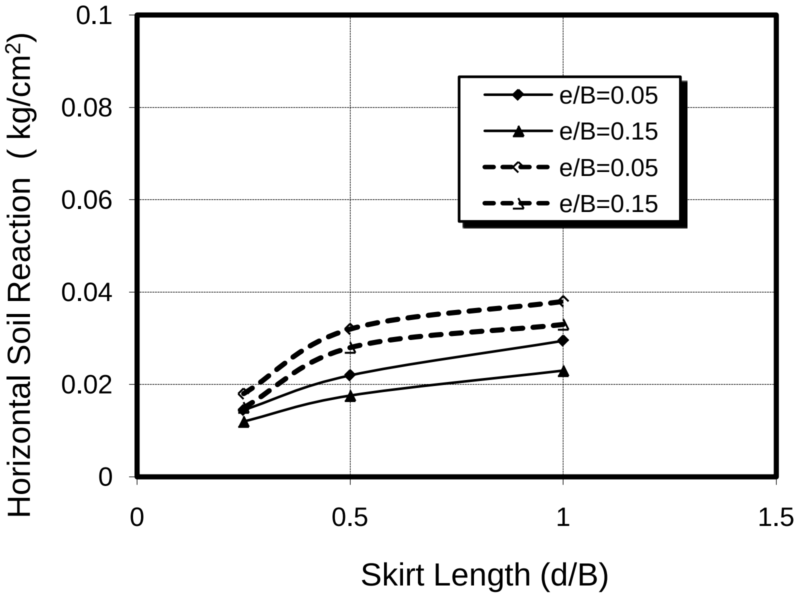


Figure 15: Variation of horizontal soil reaction at the bottom of the skirt (θ=10 º).

CONCLUSIONS

The nonlinear response of eccentrically-inclined loaded skirted strip footing has been investigated through a series of laboratory model tests and FEM analysis. Based on the results of this investigation, the following conclusions can be made:

Increasing the length of the skirt improve the load-settlement behavior. The rate of improvement increases with the increase of both load eccentricity and load inclination angle and reached its maximum value at skirt length equal to half the footing width.

The improvement ratio of the ultimate bearing capacity due to the use of skirt reached about 5.50 times that of footing without skirt.

Sliding resistance is the most critical factor in the overall stability of the flat strip footing subjected to high load inclination angle. The use of skirt enhances the footing resistance to sliding due to the horizontal soil reaction developed on the skirt side.

Increasing the skirt inclination angle increases the ultimate bearing capacity and decreases the corresponding settlement. The rate of improvement increase with the increase of load inclination angle.

The finite element software PLAXIS, Version 7.1, gives a good insight and helps in understanding the behavior of soil supporting a skirted footing under different loading conditions.

The FEM is capable of predicting the load – settlement response to a good level of accuracy except at high load eccentricity and high load inclination angle. Generally, the FEM gives higher values than the experimental results.

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