Behavior of skirted strip footing under eccentric load

Comportement de strippe footing siroté sous charge excentrique

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ABSTRACT

Construction of vertical skirt at the base of the footing, to confine the underlying soil and generate a soil resistance on skirt side that helps the footing to resist sliding, is one of the recognized bearing capacity improvement techniques. In this research, laboratory investigation combined with numerical analysis was performed to study the behavior of one sided skirted strip footing subjected to eccentric load. A range of load eccentricities and skirt lengths were investigated. Bearing capacity values for all cases were compared to come up with the favorable design conditions.

RÉSUMÉ

Construction d'une sirote verticale à la base du footing pour confiner le sous sol et de générer une résistance du sol sur la coté du footing qui permet de résister à un glissement est une technique bien reconnue pour améliorer la capacité portante. Dans cette recherche, une investigation au laboratoire combinée avec une analyse numérique a été réalisée pour étudier le comportement d'un coté du footing soumis à la charge excentrique. Une gamme d'excentricités de charge et des longueurs de sirote ont été étudiés. Les valeurs de la capacité portante pour l'ensemble des cas ont été comparées pour établir la conception des conditions favorables du design.

Keywords : skirted footing, laboratory model, numerical analysis, eccentric load

1 INTRODUCTION

Soil pressures below shallow foundations and earth retaining structures subjected to moments due to oblique or eccentric loads generally are not uniform. The non-uniformity of the soil pressure tends to tilt the footing. This tilt increases with the increase of load eccentricity, and consequently the bearing capacity is reduced. As a result, the designer enlarges the footing, and that raises the cost of foundation beyond economical values.

Recently, using a ring beam or a skirt as soil improvement technique had been investigated by many researchers (Mahiyar and Patel, 2000; Martin, 2001; Ortiz, 2001; Boushehrian and Hataf, 2003; Micic et al, 2003; EL Sawwaf and Nazer, 2005; Al-Aghbari and Zein, 2006). They found that the bearing capacity increases with increasing the skirt length, and the skirt resists lateral displacement of soil underneath the footing leading to a significant improvement in the footing response and noticeable reduction in footing settlement. The settlement improvement is a result of the restraining action to soil lateral deformation created by the presence of the skirt.

Kurian and Devi (1997), Bransby and Randolph (1999), Hu et al. (1999), Gourvenec (2002, 2003) used the FEM to study the effect of using a skirt to prevent the tilting of footing due to eccentric loading. Their results indicated an overall enhancement in the bearing capacity of circular skirted footing compared with the plain footing, as well as a noticeable reduction in settlement.

The scope of the conducted research comprised an experimental investigation and a numerical simulation. The study was performed to evaluate the effect of providing a single skirt to a strip footing at the near edge to an eccentric vertical load. Numerical analysis was carried out using the finite element software PLAXIS, to evaluate the efficiency of the numerical analysis by comparing the load-settlement responses from the model footing test data and the FEM.

2 LABORATORY INVESTIGTION

2.1 *Footing model*

A laboratory strip footing model was assembled in a test tank with inner dimensions of 200 cm 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 10mm thick, fixed by rigid frames and restrained by steel stiffeners to keep plane strain conditions during testing, as shown in Figure 1. The footing model used is 200mm rigid steel plate with a rough base spanned the width of the tank. 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 hydraulic jack were used to apply the load to the footing through 50-KN proving ring. The tank was filled with poorly graded medium sand. Most of the model tests were conducted at a relative density of 60 % where the friction angle was about 40° as determined by a direct shear test.

2.2 *Testing program*

A predetermined weight of dry sand was poured in the tank and compacted in layers to satisfy the targeted relative density. The accuracy of sand density inside the tank was checked by conducting three preliminary density tests. The variation of sand relative density was found to be 60% ±3%. The model strip footing was fixed to the skirt. The load was slowly applied at the required eccentricity, using a hydraulic jack.

Soil displacements were observed by means of photographic measurements. Close-range photogrammetry was used to

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measure the displacement of individual soil grains to an accuracy of 5 microns. During the tests, a lot of needles between the sand layers were placed .The needles were used as markers in the soil to exactly trace its movements. The photographs were taken from a distance of 1.5 – 2.0 m. The camera shots were inserted in a computer program designed for measuring the soil movements.

Figure 1. Test tank.

Skirt length, load eccentricity and soil relative density were the main variables in these tests. A series of 20 experimental model skirted strip footing tests was carried out for eccentrically vertical loaded footing, with and without skirt, and supported by sand compacted to a relative density of 60%. The load eccentricity, e, varied from zero to 35% of the footing width, B, (i.e. e = 0.0, 0.05B, 0.15B, 0.25B and 0.35B). The skirt length, d, was varied from zero to B (i.e. d = 0.0, 0.25B, 0.50B, and B). Also, eight tests were carried out on strip footing, with and without skirt, and supported on sand with relative density of 35%, 50%, 60% and 75%.

3 LABORATORY TEST RESULTS

3.1 *Load – settlement relationship*

Examples of the load–settlement curves for skirted footing supported on sand compacted to a relative density of 60 %, are shown in Figure 2. These curves were plotted for different values of load eccentricity e/B and skirt length d/B. It was obvious that increasing the skirt length improved the load-settlement behavior. The particles of cohesionless soil under a footing tended to move laterally towards the closer edge of the eccentric load. Inserting a vertical skirt on this side restricted the soil from moving laterally, and consequently prevented the footing from tilting**.** The increase in skirt length led to more resistance to soil lateral movement. The skirt was more effective in reducing the soil movement at higher load eccentricity.

The results indicated that in case of concentric load the increase in the skirt length led to a decrease in the bearing capacity at the same settlement level compared to plain strip footing. This is due to the fact that the skirt can sustain loads by end bearing and side friction. The skirt behaved as a support to the footing from one edge only. As a result, the footing rotated and the rotation increased with the increase of skirt length which led to a decrease in the bearing capacity.

3.2 *Footing rotation*

One of the main objectives of the present study is to prevent or decrease footing tilt due to eccentric load by providing a single skirt as an integral part of the footing at the edge close to the eccentrically loaded side. Figure 3 shows an example of the load–rotation relationships. Results indicated that the increase in skirt length led to a decrease in footing rotation. The rate of improvement in the load-rotation relationship increased with the

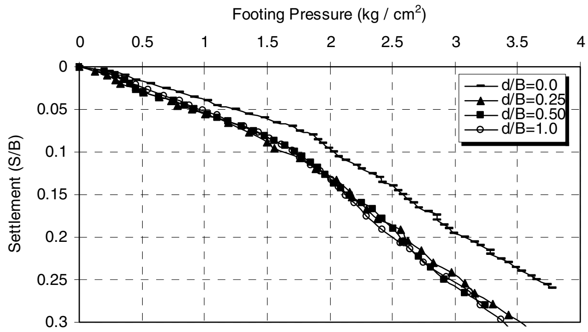

Figure 2a. Settlement curves for footing subjected to concentric load

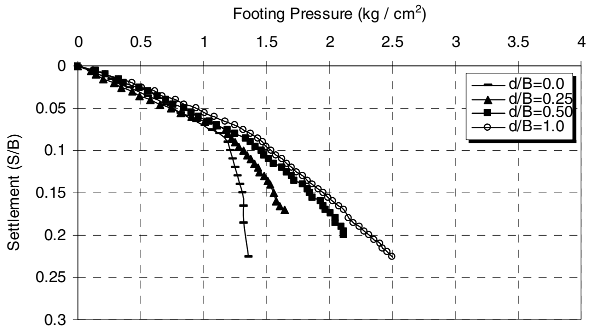

Figure 2b. Settlement curves for footing subjected to eccentric load at e/B=0.15.

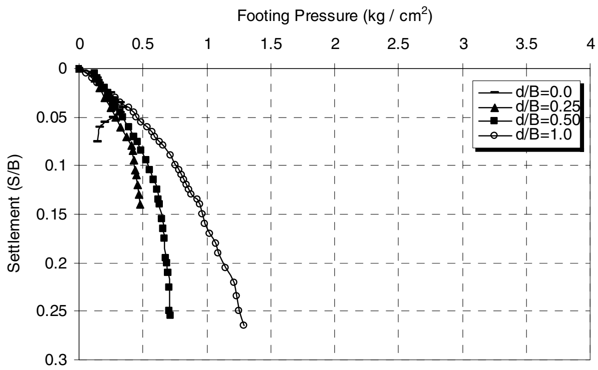

Figure 2c. Settlement curves for footing subjected to eccentric load at e/B=0.35.

increase of load eccentricity. The skirt improved the footing rotation behavior by almost 4.0 times the footing without skirt. The footing with skirt length of d/B=0.25 and 0.50, subjected to eccentric load out of the middle third, lost some of its contact with soil at stress level 30 % higher than the case of footing without skirt. When the skirt length was increased up to the footing width, the footing didn't lose its contact with the soil.

3.3 *Ultimate bearing capacity ratio*

The increase in the ultimate bearing capacity in case of skirted footing compared to footing without skirt can be best expressed in terms of dimensionless parameter called the Ultimate Bearing

Capacity Ratio (BCR_U). When BCR_U was plotted against load e/B for different values of d/B (Fig. 4), the results showed an increase in BCR_U with the increase in the skirt length, reaching its maximum value at d/B = 1/2.The skirt effect is more pronounced at high load eccentricity where the improvement reached about 82%.

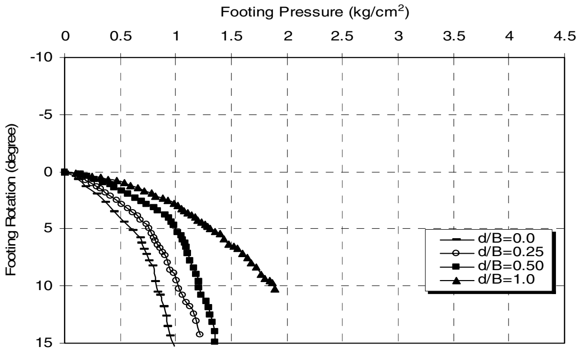

Figure 3. Rotation curves for footing subjected to eccentric load at e/B=0.25.

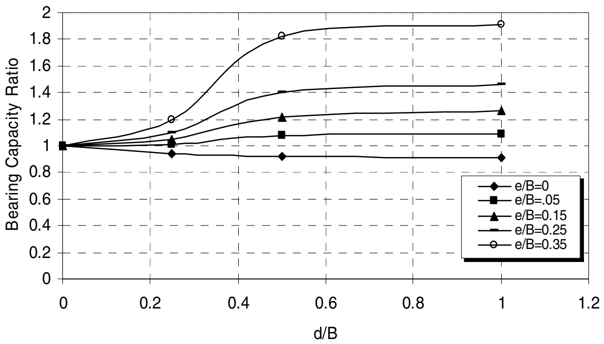

Figure 4. Improvement in ultimate bearing capacity ratio.

3.4 *Effect of soil density*

Load–settlement and load-rotation curves when plotted for the skirted strip footing supported on sand compacted to different relative densities (Dr = 35, 50, 60, and 75 %) showed that using a skirt at low relative density (Dr = 35%) reduced the settlement by about 50%. With the increase in soil density, an enhancement occurred in the soil behavior but with less degree than the case of loose soil. This was possibly because the dense sand restricted the movement of soil under the footing more than loose sand. Also, the results indicated that in loose and medium state, the skirted footing could resist rotation up to 5.0 times the footing without skirt. However, in the dense state, the skirt has no effect in the elastic state of loading. This was due to the increase in interlocking between soil grains in the dense state which decreased the soil movement and settlement.

4 NUMERICAL ANALYSIS

The finite element method, FEM, could be utilized for identifying the patterns of deformations and stress distribution in soil. Monitoring the soil behavior under applied loads for a long time is rather expensive, thus the use of numerical analysis is useful to predict the soil behavior throughout its life time. The FEM gets more powerful as its results are verified with experimental results. In this research, the elasto – plastic finite element analysis was carried out using the commercial program PLAXIS version 7.1 (Brinkgreve and Vermeer 1998). 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 as a roller condition. The base horizontal boundary was constrained in both the horizontal and vertical directions. The sand was modeled using a hyperbolic model; the hardening soil model. This model has the following basic characteristics: (a) stress dependent stiffness according to a power law, (b) hyperbolic relationship between strain and deviatoric stress, (c) distinction between primary deviatoric loading and unloading/ reloading, (d) failure behavior according to the Mohr-coulomb model, and (e) an elasto- plastic model. The soil model parameters used in the finite element calculation (Table 1) were derived from a series of a laboratory drained triaxial compression tests. Poisson's ratio was kept constant at 0.30 for all the calculations which based on the application of load rather than prescribed displacements.

Table 1. Soil parameters used in the numerical model.

Parameter	Value
Unit weight, γ (g / cm^3)	1.76
Angle of internal friction, Φ °	40
Cohesion, c (kg /cm^2)	0
Failure ratio, R_f	0.9
Angle of dilatancy, ψ degree	8.0
Power for stress-level dependency of stiffness, m	0.60
Secant stiffness in standard drained triaxial test, E_{50}^{ref}(kg/cm^2)	200

5COMPARATIVE STUDY

The load–settlement relationships from both experimental and numerical analysis for skirted footing (d/B = 0.50) subjected to vertical load at different load eccentricities (e/B = 0.0, 0.15, and 0.35) are demonstrated in Figure 5. There was a satisfactory agreement between the FEM simulation and the experimental results. The overall trends of the settlement curves were similar, except at high load eccentricity (e/B = 0.35). In most cases, the predicated footing pressure from FEM was greater than that from the experimental results. The FEM results indicated that the ultimate bearing capacity ranged from -22 % to +29 % of the experimental results.

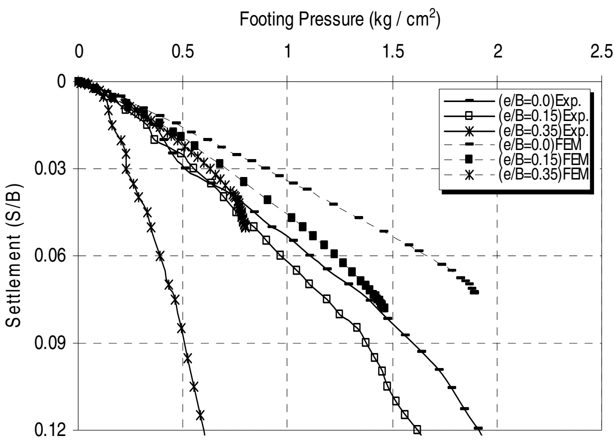

Figure 5. Comparison of settlement curves for skirted footing with d/B=0.50 and subjected to vertical eccentric load.

Generally, the experimental work and FEM had the same trend where the ultimate bearing capacity decreased with the increase in load eccentricity. This was due to that the eccentric load forced the footing to rotate, which was the main reason of the ultimate bearing capacity reduction. Figure 7 shows the direction of soil movement illustrated by the velocity field of the skirted footing (d/B=0.50), subjected to eccentric load (e/B= 0.35).

The soil movements at any stage of loading could be determined from both the experimental work and the FEM. In the experimental model, the load was applied in small increments and the corresponding footing displacements were recorded by dial gauges. Camera shot was taken at the beginning of the test (at load=zero) and at the ultimate bearing capacity (failure load). The point of failure was determined from the load-settlement curve. The two concerning photographs which represent the initial and the failure load are placed in their position on the computer program where the true displacement can be determined. The soil movements at failure load of the experimental tests and the FEM are qualitatively agreed without exact equalization of the obtained values (Fig. 8).

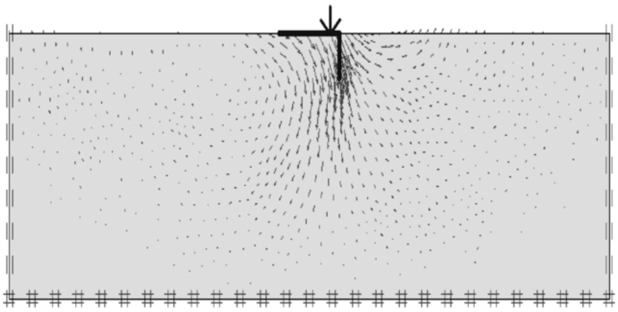

Figure 7. Velocity fields for skirted footing (d/B=0.50) subjected to eccentric vertical load (e/B=0.35).

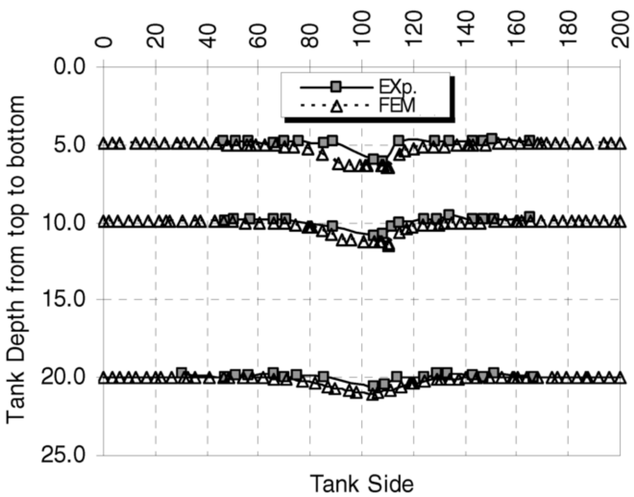

Figure 8. Soil movement at different depths under skirted footing for loading condition; d/B=0.50 and e/B=0.05.

6 CONCLUSIONS

Based on the results of this research, the conclusions are:

1. The skirt length, when increased, the footing settlement was reduced. The reduction rate improved with the increase of load eccentricity.
2. Under eccentric load, the skirt improved the footing resistance to rotation up to 5.0 times the resistance of the plain footing.
3. The skirt enhanced the footing behavior supported by loose and medium sands. However, in the dense state the skirt had no effect in the elastic state of loading. Its effect started at the failure load.
4. The ultimate bearing capacity ratio increased with the increase in the skirt length, and reached its maximum value at skirt length equal to half of the footing width.
5. In case of concentric load, the increase of the skirt length led to a decrease in the bearing capacity.
6. For skirted footing, PLAXIS 7.1 was a good tool in understanding the soil behavior under different loading conditions. Although it generally gave higher values than the experimental results, it was capable of predicting the load–settlement relationship with enough accuracy, except at high load eccentricities.

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