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Experimental Evaluation of Bearing Capacity of Skirted Footings

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Abstract Structural skirts have been used underneath shallow foundations of marine structures for many years, due to their stability advantages. However limited knowledge is available on the performance of the skirted foundations when it comes to their usage as conventional shallow foundations. In this research study the bearing capacity of such foundations was evaluated through laboratory testing. In this context the effects of skirt stiffness and depth on the bearing capacity of skirted footing models were investigated. The test results were then compared with various bearing capacity equations. It was found that using structural skirts may improve the footing bearing capacity up to 3.68 times depending on the geometry and structural specifications of the skirts and footings, soil characteristics and conditions of both soil-skirt and soil-footing interfaces.

Keywords Bearing Capacity, Skirted Footings, Shallow Foundations, Dense Sand

1. Introduction

The problem of bearing capacity of shallow foundations has been widely discussed in the geotechnical engineering literature. Till now numerous methods have been presented for determination of bearing capacity of foundations embedded in soils. Most of conventional methods are based on a limit equilibrium approach. Based on the limit equilibrium theory, a general shear mechanism is assumed within homogeneous soil underneath a strip footing. The footing bearing capacity is then determined based on static equilibrium of the soil wedge formed underneath the footing. Thus the amount of bearing capacity is directly dependent on the length of slip lines i.e. more lengthy slip lines yield greater bearing capacity. An increase in the length of slip lines may be achieved by increasing either the footing width or embedment depth (Das, 2007). Usage of structural skirts which encompass the soil underneath footing may also be a reasonable method to increase the length of slip lines (Figure 1 with B width of footing and D_s depth of skirt). Using this type of foundation may also reduce the cost of foundation construction as the amount of excavation and filling operations reduces for the skirted foundations in comparison to those of conventional foundations. Furthermore using peripheral skirts can prevent the soil beneath foundation from squeezing out and any damage due to excavations for adjacent construction works is minimized. Considering the potential advantages of skirted foundations, it seems using these foundations may make a great difference in the cost and performance of foundations. Meanwhile, more investigations must be carried out on the bearing capacity and settlement behavior of the skirted foundations to highlight their advantages for practicing engineers. Several research studies relevant to this subject will be reviewed in the following section.

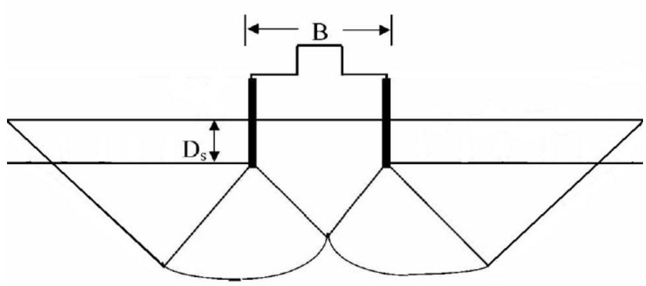

Figure 1. Increase in length of slip lines due to using of skirt

Bransby and Randolph (1998) and Hu et al. (1999) described the applications of marine skirted foundations and their computational methods in details. Bransby and Martin (1999) introduced a work-hardening model for performance of bucket foundations, under combined loading consisting of vertical, horizontal and moment components. They presented a method in combination with the analysis method of bucket foundations for jacket structures and validated it through centrifuge modeling. The results of centrifuge model tests were then compared with results of numerical analyses from which a good agreement was concluded between these results. Gourvenec (2002) studied the strip and circular skirted foundations on non-homogenous marine clay under combined loading using two and three dimensional finite element analyses.

Acosta-Martinez et al. (2008) reported the experimental results of a shallow skirted foundation under compression and tension loads. The foundation performance was considered under both permanent and transient loadings. Also the effects of consolidation stress level and stress history on foundation undrained bearing capacity and permanent load response were investigated. Gourvenec and Randolph (2010) examined consolidation beneath circular skirted foundations. They used small strain finite element analysis for quantifying fast and time dependent responses of circular skirted foundations under vertical single-axial loading. Foundations with frictionless boundaries and quite rough soil-skirt contact as well as various ratios of embedment depths to diameter were investigated and their responses were compared with those of shallow foundations. It was found that both embedment and boundary friction have major effects on the foundation consolidation response.

Al-Aghbari and Mohamedzein (2004) proposed a modified bearing capacity equation for skirted strip foundations on dense sand based on the results of experimental study on skirted footing models. Several factors such as foundation base friction, skirt depth, skirt side roughness, skirt stiffness and soil compressibility were considered in this study and their effects incorporated in the bearing capacity equation. Based on their experimental studies they concluded that structural skirts can improve the foundation bearing capacity by a factor of 1.5 to 3.9.

Al-Aghbari and Mohamedzein (2006) studied the performance improvement of circular foundations using structural skirts through loading test models. It was found that this type of reinforcement increased the bearing capacity of base soil and improved the footing load–displacement response. Also it was found that the structural skirts reduce the settlement of surface footings compared with footings without structural skirts. At a bearing pressure equal to 50% of ultimate bearing capacity, the footing settlement reduced to about 11% that of footing without skirt. Al-Aghbari (2007) studied settlement of shallow circular foundations with structural skirts resting on sand. The experimental results showed that using skirted footing reduced the settlement of bed soil and improved the stress-displacement behavior of the footing. A settlement reduction factor (SRF) was proposed, which took into account various parameters effective on footing settlements. It was found that the use of structural skirts led to settlement reduction in the range of 0.1 to 1.0 depending on the applied load and skirt depth.

Nighojkar et al. (2010) studied the performance of bi-angle shaped skirted footing under two-way eccentric loads. They concluded that the differential settlement of extreme corners of the footing is affected considerably due to presence of skirts. Skirts have been found to be helpful in reducing differential settlement due to eccentric loading.

As noted above, most of previous studies were devoted to skirted foundations for marine structures. Although some experimental studies focused on strip skirted footings as conventional foundations, they involved only with partial peripheral skirts. This paper reports the results of an experimental study on the performance footing models with full peripheral skirts in various conditions.

2. Testing Setup and Materials

Loading tests were performed on skirted model footings embedded to sand in a test box encased within a rigid steel frame. Regarding to the span of available loading frame, a test box with interior size of 440×420×450 mm was selected. The test box consisted of a steel rigid floor and two wooden sides with metal braces, while other sides were built of 10mm thickness Plexiglas with steel bar supports, to prevent them from lateral expansion. The internal faces of wooden sides were covered with a thin layer of smooth plastic to prepare it for lubrication. To minimize boundary friction, all of the internal faces of side walls were greased and left for at least one hour to allow the uniform spreading grease over the surface (Yung et al., 2004). Model footings of 70mm width were adopted based on the box dimensions to avoid of rigid walls effects on the footing bearing capacity (Bowles, 1996; Salençon, 2002). The footings were made of aluminum plates which their typical specifications are shown in Figure 2. Each skirted footing consisted of a rigid base with more than 25mm thickness and a skirt made of aluminum plate shaped as box profile. The rigid footing could be fixed to the skirt by several proper screws during the model placement in the sand. To maintain plane strain condition within soil underneath the model footing, the box width was limited nearly to the size of the footing length using two steel profiles of 80mm width. In such a condition each end of the footing is located at near adjacent of the steel profile and prevents soil displacement in the longitude direction. Thin lubricated films were placed at the contact surfaces of the footing ends and the steel profiles to eliminate friction at their interfaces.

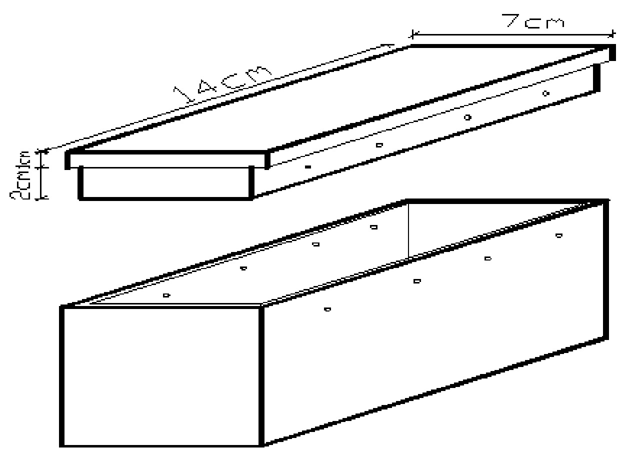

Figure 2. Specifications of Skirted Footing Model

2.1. Materials

A sandy soil was used in this experimental investigation.

The grading curve of this sand is shown in Figure 3. The sand grading characteristics D_{10}, D_{30}, D_{60} were determined 0.25, 0.47, and 0.85mm respectively. These yielded uniformity coefficient, C_u, 3.2 and curvature coefficient, C_c, 1.04. Thus the sand was classified as uniform or poorly graded sand, SP, based on unified soil Classification system.

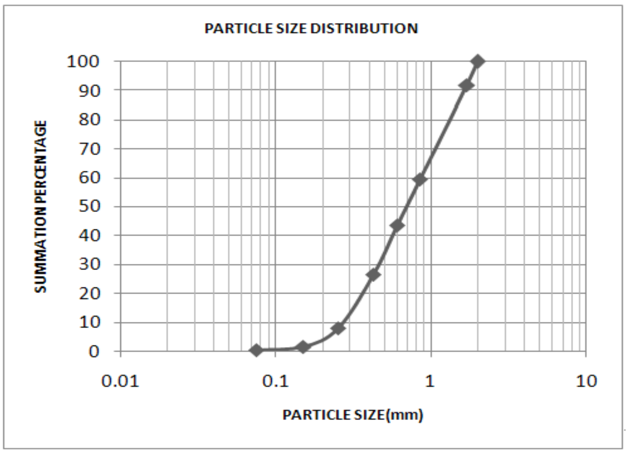

Figure 3. The grading curve of used sand

The specific gravity of the sand was measured 2.7. The minimum and maximum dry unit weights of the soil were obtained as 16.28kN/m^3 and 18.69kN/m^3 respectively. Using sand raining technique a medium dense state was achieved at unit weight of 17.67kN/m^3 which equals to relative density of 61%. Achievable density in this technique depends on the precipitation intensity and uniformity of sand rain as well as height of fall (Cresswell et al., 1999). The test density was achieved when the sand spilled within the test tank at flow rate of 22g/sec through a funnel from constant height of 20cm.

The strength properties of the sand were determined through direct shear tests. These tests were carried out at normal stresses 39, 54.76 and 86.22kPa on 63mm diameter samples at shear displacement rate of 1.06mm/min. The average value of peak friction angle of the sand was found to be 42º. In footing load tests proper sand paper was glued to inner and outer sides of skirt as well as bottom face of footing to provide rough contacts with sand. Friction angle between the test sand and the abrasive paper was determined 36º over the same normal stresses using the direct shear apparatus. This value of contact friction angle is approximately equal to the friction angle between concrete and soil $(\delta \approx \mathbf{0.9}\varphi)$ and this may simulate the conditions of real foundations.

2.2. Test Procedures

Enough sand height was required to avoid of likely effects of rigid bottom of test box on the footing bearing capacity. Thus several loading tests on a typical model footing were carried out at various cases of sand layer height within the test box. The test results in terms of the footing bearing capacity versus the sand height have been shown in Figure 4. These results showed that for sand thickness greater than 4B the footing bearing capacity sympathized nearly to a constant value (B; width of model footing). Thus the sand fill of 4B height was placed within the test box to omit any effect of the box rigid bottom on the footing bearing capacity.

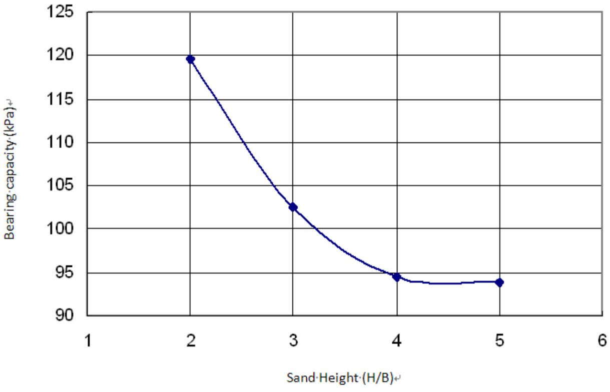

Figure 4. Footing Bearing Capacity versus the Relative Sand Bed Thickness on Rigid Base

To carry out each loading test, all internal faces of the test box walls were properly lubricated. The box was then placed within the loading frame of the triaxial apparatus and filled with sand. The sand placement was made by sand raining technique to reach the required height of 4B and its top surface was leveled gently by a light thin ruler. The footing skirt was then placed centrally across the width of the box. The sand raining continued simultaneously into the skirt and the test box to the level predicted for footing base. After leveling the sand surface within the skirt, the base was carefully fixed on the skirt by 8 screws. The model footing was then subjected to centric vertical loading using a displacement control apparatus at rate of 1 mm/min. The applied load was recorded by a 30kN proving ring with precision of 10N at every 0.5mm settlement. Figure 5 shows various stages footing placement into sand bed and loading test. Repeatability of tests was also considered and although the difference in the results were mostly less than 5%, the mean values of three replications of each test were employed to achieve more accurate results.

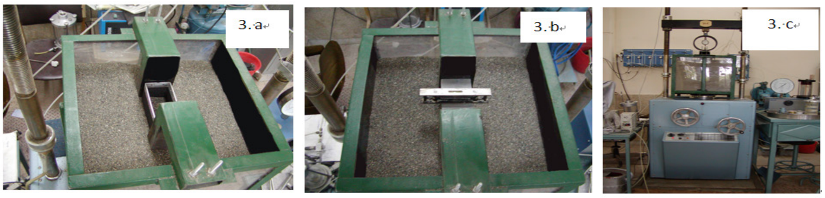

Figure 5. Test Preparation Sequences; a) Skirt Placement, b) Matching Base Footing, c) Load Application

3. Research Results

3.1. The Effect of Skirt Thickness

To investigate the effect of structural skirt's thickness on the bearing capacity of the skirted footings, three types of skirts with 1, 3 and 5 mm thickness were selected. The embedment depth of the skirted footing for these testing cases was selected as 1B which corresponds to a depth ratio of D/B=1. The skirted footing was then subjected to displacement control loading and the applied loads were recorded from a dial gauge at 0.5mm settlement increments. Figure 6 shows the stress-settlement relationship for the skirted footings with various thicknesses of structural skirts. As it is evident from Figure 6, stress-settlement curves of the footings with 3 and 5mm skirt thickness were matched well with each other, and show nearly the same ultimate bearing capacity and slope trend, while the load bearing curve of footing with 1mm skirt thickness was different. The stress-settlement curve for 1mm skirt thickness footing follows initially the same path of other curves but shows much lower slope changes than the other curves at high settlements. Furthermore unlike the two other curves, the slope change occurs smoothly so that no distinctive discontinuity point may be determined in this case. In fact, the stress-settlement curve of 1mm skirt thickness footing passes smoothly through the break point of the curves of 3 and 5mm skirt thickness footings, and shows greater bearing pressure at high settlement values. This may attributed to the lateral expansion of the 1mm thick skirt at high stress levels. This lateral expansion is associated with an increase of foundation width at bottom level of skirt and thus bearing pressure shows a linearly increasing trend.

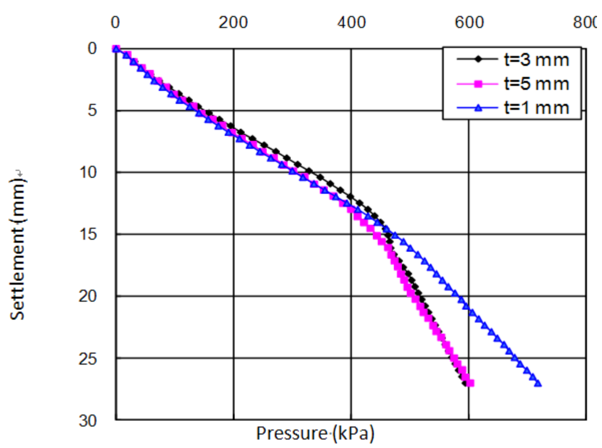

Figure 6. Pressure-Settlement of Skirted Footing for Various Skirt Thicknesses

3.2. Effects of Embedment Depth

In this section the effect of embedment depth of skirt on the bearing capacity of model footings was investigated. Several loading tests were carried out for different skirt dept ratios (D/B) of 0.5, 1 and 1.5. The test procedures were the same as described in previous section. It should be mentioned that, in all cases, for preventing the rigid base effects on the tests results, the test box was filled with sand to the height of 4B (280mm) and the skirt was then placed on the leveled surface of sand. The stress-settlement data obtained from these tests are presented in Figure 7. All of the pressure-settlement curves show nearly the same initial slope but involve different failure point from which the footing settlement increases linearly at a relatively high slope with pressure increase. The pressure failure point (the pressure corresponding to discontinuity point at pressure- settlement curve) was determined as the footing ultimate bearing capacity. The ultimate bearing capacity values and corresponding settlements have been presented in table 1 for the model footings. Figure 8 shows the variations of the footing ultimate baring capacity versus the skirt depth ratio $\left(\frac{D}{B}\right)$. As it is seen, this relation is non-linear i.e. with more pronounced increasing effects on bearing capacity at higher depth ratios. In fact, the rate of increase in the bearing capacity due to increasing depth ratio from 1 to 1.5 is much higher than that caused by increasing the depth ratio from 0.5 to 1.

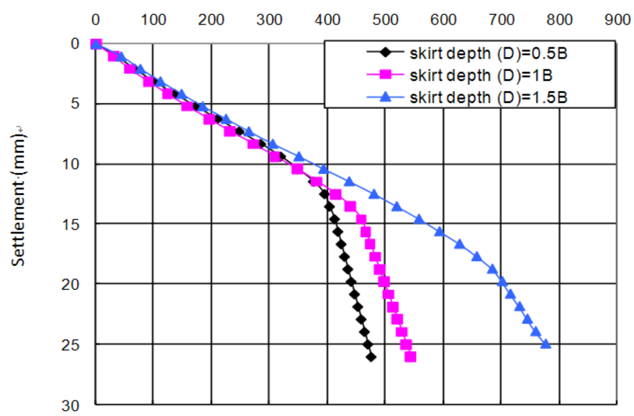

Figure 7. Pressure-Settlement of Skirted Footing for Different Depth of Skirts

Table 1. Bearing capacity and settlement of strip skirted foundations with different height of skirts

Skirt height	q_{ult} (kPa)	Failure Settlement (mm)
0.5 B	388	12
1 B	463	15
1.5 B	685	18.5

3.3. Comparison with Conventional Methods

Bowles (1996) introduced four sets of ultimate bearing capacity equations as the most popular methods for foundation design calculations. These methods are included of Terzaghi (1943), Meyerhof (1963), Hansen (1970), and Vesic (1973) methods. All of these methods are based on limit equilibrium theory with some differences in their assumptions regarding slip surfaces and loading conditions.

Here, the ultimate bearing capacity of shallow foundations with the same embedment depth as the skirt height was calculated using the conventional methods. An improvement ratio was then determined as the ratio of the experimentally determined ultimate bearing capacity of the skirted model footings to the calculated value of ultimate bearing capacity of foundations with the same embedment depth. The values of the improvement ratio for various embedment ratios are presented in table 2. It is clearly observed that using of skirt in the model footings was more effective than embedding the foundations in the same depth of skirts height. The improvement ratio of bearing capacity was averagely ranged from 2.91 to 3.68 depending on the embedment depth. Comparing with previously reported improvement ratios of 1.5 to 3.9 (Al-Aghbari & Mohamedzein), the least improvement ratio for the new skirt conditions (full peripheral skirt instead of partial skirt) showed an enhancement of nearly twofold. The results also showed that using skirted footing had the greatest efficiency at embedment ratio of 0.5. Figure 8 presents the variations of the ultimate bearing capacity of the model footing versus the embedment depth (or skirt height) from the conventional methods along with those of the experimental results. Again it is interesting to see from Figure 8 that the skirt depth has considerable effect on the footing bearing capacity in comparison with the embedment depth of conventional foundations. Furthermore, the experimental results showed that the ultimate bearing capacity increased nonlinearly with the skirt depth while the bearing values from conventional equations had an approximately linear increase with the embedment depth for the considered depth ratios.

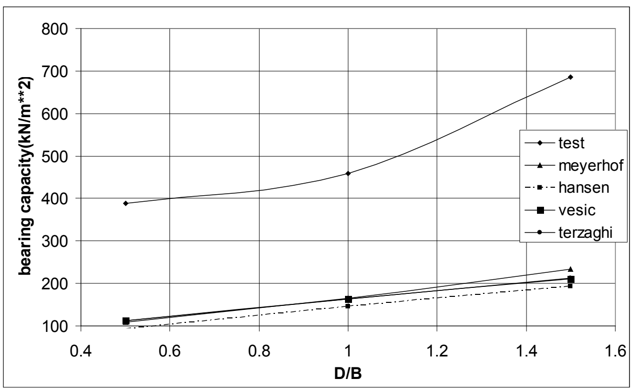

Figure 8. Variation of Bearing Capacity versus Skirt Depth Ratio

Table 2. Improvement ratio of bearing capacity using the structural skirt

	D/B=0.5	D/B=1	D/B=1.5
Terzaghi	3.46	2.85	3.22
Meyerhof	3.59	2.78	2.93
Hansen	4.18	3.19	3.55
Vesic	3.48	2.83	3.24
Average	3.68	2.91	3.24

4. Conclusions

The performance of skirted footing models in sand was investigated under vertical loading. The consideration was focused on the effects of skirt thickness and embedment depth on the footing bearing capacity and the following conclusions was made based on the obtained results:

1. Using peripheral structural skirt in combination with conventional footing improves the overall foundation performance in terms of increasing bearing capacity, lowering excavation volume, and encompassing the soil underneath footing.
2. Footing with flexible skirts showed greater bearing capacity at high settlement values while for rigid skirts (thickness above 3mm) the skirt thickness had no significant effects on the footing bearing capacity.
3. Skirting the model footings was found to be more effective than embedding the foundations in the same depth as skirts height.
4. The ultimate bearing capacity of the skirted footing was 2.91 to 3.68 times greater than the average value of the calculated ultimate bearing capacity of foundations with the same depth as skirt depth. For the new skirt conditions (full peripheral skirt lieu of partial skirt), the least improvement ratio showed an enhancement of nearly twofold (from 1.5 to 2.91).

Acknowledgments

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