EXPERIMENTAL STUDY ON BEARING CAPACITY OF SKIRTED FOUNDATIONS ON DRY GYPSEOUS SOIL

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ABSTRACT

Skirted foundations are used widely in offshore structures, either as a single foundation system for gravity based structures, or as foundations for subsea infrastructure such as manifolds. This paper demonstrates the experimental results of the laboratory testing program to investigate the optimum length to diameter ratio of skirted foundation to get maximum bearing capacity on gypseous soil of different relative density. Gypseous soil was selected from Tikrit city north of Baghdad, with gypsum content 54%. Standard tests were performed to determine the physical properties and classification. Model tests were carried out to obtain load-settlement curves for circular skirted footing models with skirt ratio (length to diameter ratio L/D) of 0, 0.25, 0.5, 0.7, 1, 1.5, 2, and 3 on soil of dry relative density 55% and 70%.

It was concluded that the presence of skirts improves the bearing capacity of the surface footing on gypseous soil. The amount of improvement increases with increasing the depth to diameter ratio of skirted footing as well as the relative density. In general, at greater L/D ratio, the lines of failure below the footing will intersect with the existence of skirt and its effect does not arrive to surface of soil. The improvement of bearing capacity is a function of length to diameter ratio of skirted footing and relative density of soil, where it increases with increase of these factors.

Keywords: Skirted footing, gypseous soil, skirt ratio, relative density.

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1. INTRODUCTION
Shallow foundations for offshore structures include skirts to satisfy bearing capacity requirement and to provide the additional horizontal resistance required by offshore environmental loading. In comparison to a surface foundation, the skirt transfers the load to deeper, typically stronger soil, thus mobilizing higher bearing capacity. Skirted foundation has been used as support for large fixed substructures or anchors for floating structures in offshore hydrocarbon development projects. Although a number of theories are available to predict the bearing capacity of shallow footings with reasonable accuracy and it seems there is a convergent prediction of bearing capacity. Unlike this, the estimation of bearing capacity of skirted foundations is based on semi empirical formulations. Researchers have tried to estimate the bearing capacity of skirted footings and parameters influencing it, using numerical analysis, theoretical formulation, model tests and prototype field tests.

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.

Tripathy (2013) presented experimental data from a series of investigations to determine the vertical and horizontal load carrying capacity of the skirted foundations at different skirt length to diameter ratio and at different relative densities. The main aim of the vertical and horizontal load test was to determine the bearing capacity and the lateral stability of the skirted foundation. Model footings of 40 mm, 60 mm, and 100 mm were selected for the test at relative density of 30%, 45%, 60%, 75%, and 90% respectively. Tests were conducted for both smooth and rough skirt footings. Smooth skirted foundations exhibited lesser bearing capacity and settlement values at failure than the rough skirted foundations at similar conditions. The enhancement in bearing capacity of skirted foundations occurred both with the increase in skirt depth and relative density of sand. The ultimate bearing capacity was found to increase with the size of the footing, the length of skirts and the relative density of sand. The failure strain was found to increase with the size of the footings and skirt length but decreases with increase in relative density of sand bed.

Mahmood (2018) conducted plain strain model tests on beds of sands with different particle size distribution (Coarse, Medium and Fine) prepared at loose state (Relative density Dr. of 30%). A strip footing model with different ratios of skirt depth to width D/B of (0.5, 1.0, 1.5, 2, and 3) was placed on the bed of sand and loaded vertically up to failure. The applied stress increments and the corresponding settlements were measured. The test results revealed that the improvement ratio increased linearly up to D/B of 1.5 then reduced. Two factors were introduce into the general bearing capacity equation where used to evaluate bearing capacity of skirt footing, there values are about 1.6 for skirt ratio ranged between 0.5 to 1.5, and 1.25 for skirt ratio more than 1.5.
This paper demonstrates the experimental results of the laboratory testing program. The objective of these tests is to investigate the optimum length to diameter ratio of skirted foundation on gypseous soil of different relative densities. This paper also presents the results of collapse potential measurement by single oedometer test performed in a standard oedometer device.

2. BEARING CAPACITY OF SKIRTED FOUNDATIONS

For shallow strip foundation with structural skirts resting on dense sand and subjected to central vertical load (Figure 1), the following modifications to the general ultimate bearing capacity equation has been proposed.

For all situations, the soil above the lower edges of the skirts should be treated as a surcharge, in a manner similar to that proposed for shallow strip foundations by Terzaghi (1943).

To determine the ultimate bearing capacity of a shallow strip foundation with structural skirts, a skirt factor ($F_y$) should be introduced into the second part of the general equation, to account for all the characteristics of the structural skirts, the soil, the foundation and the loading, which influence the ultimate bearing capacity of the foundation. No factor is included in the first part of the general equation because the effect of the skirt can be accounted for by the skirt depth. Thus the modified ultimate bearing capacity equation may be written as:

$$q_{ult} = \gamma (D_{fs} + D_s)N_q + \frac{1}{2} B' \gamma N_y F_y$$

where:

$F_y$ = skirt factor,

$D_n$ = depth to foundation base below ground level,

$D_s$ = depth to the lower edge of the skirt below the foundation base,

$B'$ = total foundation width with skirts ($B+2B_s$), and

$B_s$ = skirt thickness.

The skirt factor ($F_y$) may be written in the following form:

$$F_y = F_{yf} \cdot F_{yd} \cdot F_{yr} \cdot F_{ys} \cdot F_{yc}$$

where:

$F_{yf}$ = foundation base friction factor,

$F_{yd}$ = skirt depth factor,

$F_{yr}$ = skirt side roughness factor,

$F_{ys}$ = skirt stiffness factor, and

$F_{yc}$ = soil compressibility factor.
Figure 1  Failure mechanism in soil under continuous foundation with structural skirt based on Terzaghi (1943) assumptions (after Al-Aghbari and Mohmedzein, 2004).

3. SOIL USED

The gypseous soil was selected from Tikrit city north of Baghdad, from Mashtal abdulla with gypsum content 54%. Then it was sieved on sieve No. 4 (4.75 mm).

Standard tests were performed to determine the physical properties, classification and chemical properties of soil and the results are summarized in Tables (1) and (2). Gypsum content determination was conducted by hydration method which is based on the loss of weight as a result of heating the highly gypseous soil. The loss of weight is due to the dehydration of gypsum (Poch, 1992). This method has been advanced by Al-Mufty and Nashat (2000). They described that gypsum content can be easily estimated by oven drying of the soil specimen at (45 °C) temperature until the specimen weight becomes constant, the weight is recorded. Then, the same specimen is dried at (105 °C) temperature and the weight is recorded again. The gypsum content is calculated according to the following equation (Al-Mufty and Nashat, 2000):

\[ \chi = \frac{W_{45^\circ C} - W_{105^\circ C}}{W_{45^\circ C}} \times 100 \]  

\[ \chi = \text{gypsum content}, \]

\[ W_{45^\circ C} = \text{weight of sample at } 45^\circ \text{C}, \text{ and} \]

\[ W_{110^\circ C} = \text{weight of sample at } 100^\circ \text{C}. \]

Table 1  Chemical properties of the soil used.

<table>
<thead>
<tr>
<th>Chemical properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gypsum content %</td>
<td>54</td>
</tr>
<tr>
<td>Total sulphate content (SO₃)%</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2  Physical properties of the soil used.

<table>
<thead>
<tr>
<th>Physical properties</th>
<th>values</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity(Gs)</td>
<td>2.39</td>
<td>ASTM D 854</td>
</tr>
<tr>
<td>% Sand</td>
<td>92</td>
<td>ASTM D 422</td>
</tr>
<tr>
<td>% Silt and clay</td>
<td>8</td>
<td>ASTM D 422</td>
</tr>
<tr>
<td>Coefficient of uniformity (Cu)</td>
<td>7</td>
<td>ASTM D 422</td>
</tr>
<tr>
<td>Coefficient of Curvature (Cc)</td>
<td>2.7</td>
<td>ASTM D 422</td>
</tr>
<tr>
<td>Optimum moisture content, (O.M.C) %</td>
<td>11.2</td>
<td>ASTM D 698</td>
</tr>
<tr>
<td>Maximum dry unitweight (γ_dry)</td>
<td>16.8</td>
<td>ASTM D 698</td>
</tr>
<tr>
<td>Minimum dry unit weight (kN/m³)</td>
<td>11.5</td>
<td>ASTM D 4254</td>
</tr>
<tr>
<td>Soil symbols according to USCS</td>
<td>SW-SM</td>
<td>ASTM D 422</td>
</tr>
</tbody>
</table>

USCS refers to the Unified Soil Classification System.

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4. TESTING PROGRAM

Depending on the results of the compaction curve, three points have been chosen (two from the dry side and one from wet side) to measure the collapse potential. Four dry samples at different relative densities of 30%, 55%, 70% and 85% respectively have been tested by direct shear test to choose the relative density in this research.

Small scale circular footing of 100mm diameter and 20mm thickness with skirts of different length to diameter ratios (L/D), rested on gypseous soil within a steel container of dimensions (600*600*700)mm have been subjected to compressive loading to investigate the optimum length to diameter ratio of skirted foundation. The total number of 16 model tests can be summarized as follows: 8 models were tested under dry condition and relative density equal to 55% and 8 models were tested under dry condition and relative density equal to 70%.

The grain size distribution (sieve analysis test) for gypseous soil was carried out in dry condition according to (ASTM D 422- 98). The classification of soil is summarized in Table (2). The specific gravity was determined according to method described by ASTM D 854 (2010) standard. Distilled water is normally used for specific gravity determination, but Kerosene is recommended instead of distilled water when the soil specimens contain a significant fraction of organic matter or gypsum material (Head, 1980; ASTM D854, 2010).

5. MODEL TEST SYSTEM

The system consists of the following parts:

1. Soil container (600x600x700) mm.
2. Steel frame and hydraulic compression handle jack.
3. Load cell.
4. Digital weighting indicator.
5. Metal footing.

The steel loading frame was manufactured to support the piston of hydraulic jack of 10ton capacity and the load is applied by running the piston downward. A manual system is suspended at the right column of the frame to control the flow of the hydraulic jack as illustrated in plate (1).

Plate 1 Steel frame and hydraulic compression handle jack.
A compression load cell (model: SM 600E) was utilized to measure the load. A digital weighting indicator was used to record the amount of applied load (model SI 4010).

Seven skirted foundations with deferent length to diameter ratios (0.25, 0.5, 0.7, 1, 1.5, 2, and 3) were used. The metal footing was situated in a position so that the center of the footing coincided with the bed soil center and in contact with the top surface of the soil. Two steel wings with 2mm thickness were welded to the edge of the footing for supporting the dial gages which are attached to the sides of the soil container with two magnetic holders.

6. TEST MODEL PREPARATION

The amount of gypseous soil used in the container was determined according to the relative density (55% and 70%). The steel container of depth 700 mm is divided into six layers; each layer is 100 mm in height.

The homogenous dry soil was placed and compacted in five layers; the layers were placed with 100 mm depth to reach a full depth of 600 mm. Specially designed hammer was used to compact the soil in the box to reach the required density. Each layer was scratched by a spatula in order to provide a good contact between the compacted layers.

After completing the last layer of the bed soil, the skirted foundation was driven into soil until the footing reach to surface of soil. Two dial gauges of 0.01mm resolution were placed at the footing edges and attached to the sides of the box by two magnetic holders. The load was applied in increments at a rate 1 mm/min until reaching 20% strain as recommended by Head (1980).

7. RESULTS AND DISCUSSION

7.1. Results of Standard Tests

7.1.1. Compaction Test

Figure (2) presents the standard compaction curve of the gypseous soil used in the study; the test was conducted according to ASTM D 698-12 specification. The compaction process increases the soil-strength, bearing-capacity and decreases the permeability, the soil-shrinkage and compressibility because of the reduction in void-ratio.

![Compaction curve for Tikrit soil (χ =54%).](image)

Figure 2 Compaction curve for Tikrit soil (χ =54%).
7.1.2. Direct Shear Test Results

Two samples were tested in the direct shear apparatus at relative density 55%, and 70% at dry condition. A summary of results for the direct shear test is presented in Table (3).

The results show that the increment of relative density (Dr) led to increment of the angle of internal friction of soil, which means a more compacted structure of soil; which is clearly shown by the reduction in soil porosity, hence more contact points develop between particles and friction surfaces that led to increase the shear strength for the same loading status.

<table>
<thead>
<tr>
<th>Relative density (D_r) %</th>
<th>Angle of internal friction, $\phi$</th>
<th>Cohesion (kN/m$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>55</td>
<td>38.4</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>41.3</td>
<td>0</td>
</tr>
</tbody>
</table>

7.2. Results of Model Tests

Typical load-settlement curves for circular skirted footing models with skirt ratio (length to diameter ratio) of 0, 0.25, 0.5, 0.7, 1, 1.5, 2, and 3 on soil of dry relative density 55% and 70% are illustrated in Figures (3) and (4), respectively. Analysis of the results revealed that the presence of skirts improves bearing capacity of the surface footing on gypseous soil. The amount of improvement increases with increasing the depth to diameter ratio of skirted footing as well as relative density.

Figure 3 Stress-settlement behavior of skirted footing on dry soil at relative density 55%.

Figure 4 Stress-settlement behavior of skirted footing on dry soil at relative density 70%.
At a higher relative density ($D_r=70\%$) for ordinary models and skirt ratio 0.25, the stress reaches a peak value at low strain and sudden failure occurs, but at lower relative density ($D_r=55\%$), the stress continues to rise non-linearly with strain. While comparing the skirted footing with the ordinary footing, it is revealed that the failure stress of skirted footing is higher than ordinary footing. At higher densities, there is no sudden failure; the stress reaches a peak value, after the bearing value reduces gradually.

In general, at greater L/D ratio, the lines of failure below the footing will intersect with the existence of skirted and its effect does not arrive to surface of soil causing confinement to soil inside the skirted and this led to increase of bearing capacity.

In the special case when L/D=3 in medium relative density, the bearing capacity is less than the bearing capacity of L/D=2. This can be attributed to that increase the confinement of soil inside the skirted is greatly increased and led to occur of dilation to soil and reduce the shear strength and decrease of bearing capacity.

Comparing the load settlement curves for high dry relative density; Figure (8), it can be observed that at L/D=0 to L/D=2, there is peak failure. The failure occurs like general shear failure, otherwise at L/D=3, there is no peak failure. The failure occurs like local shear failure due to increase in confining pressure with depth.

To select the failure criterion, the ultimate bearing values are taken at 10% strain for footings inserted in gypseous soil of low relative densities, where no definite peaks are available, and for higher densities, the failure criterion is that the ultimate bearing capacity is considered at peak stress value. Further, it is noticed that the stiffness (slope) of the load-settlement curves increases with either increase in the skirt ratio and relative density.

The results of this study show that skirted footings demonstrate bearing capacity and settlement values close, but not equal, to those of embedded foundations of the same length and diameter. The improvement in bearing capacity increases with increasing the depth of footing and increase in relative density of gypseous soil. At relative density 70\% in ordinary footing and skirt ratio 0.25, there is a peak failure occurs at low strain, while at other skirt ratios, there is a peak failure occurs at high strain expect at skirt ratio 3 where there is no peak failure and the failure load is taken corresponding to 10\% strain.

### 7.3. Effect of relative density of gypseous soil

Figures (5) to (12) illustrate the stress-settlement relations for skirted footing of different L/D ratios resting on gypseous soil of two different relative densities.

From Figures (5) to (8), the bearing capacity of ordinary footings are (221) and (273) kPa for dry relative density of 55\% and 70\%, respectively, and the bearing capacity for skirted ratio 0.25 are (259) and (291) kPa for relative density 55\% and 70\%, respectively. The peak values for L/D=0 and L/D=0.25 is at 5 mm settlement, while the bearing capacity for L/D=0.5 are (313) and (490) kPa for relative densities 55\% and 70 \%, respectively, and the bearing capacity for L/D=0.7 are (355) and (522) kPa for relative densities 55\% and 70\%, respectively, and the peak values at 10\% strain.

From Figures (9) and (10), the bearing capacity for footings with skirt ratio L/D=1 and L/D=1.5 for 55\% relative density are (394) and (431) kPa, respectively, and for 70\% relative density are (538) and (546) kPa, respectively.

From Figures (11) and (12), the bearing capacity for footing of skirt ratio L/D=2 and L/D=3 for 55\% dry relative density are (496.5) and (425) kPa respectively, and for 70\% relative density are (552) and (630) kPa, respectively. For footings of skirt ratio L/D=3 at 70\% relative density, there is no peak value due to increase of confinement.
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Figure 5 Stress-settlement relation for skirted foundation with L/D=0 on soil at different relative densities.

Figure 6 Stress-settlement relation for skirted foundation L/D =0.25 on soil at different relative densities.

Figure 7 Stress-settlement relation for skirted foundation L/D=0.5 on soil at different relative densities.
Figure 8 Stress-settlement relation for skirted foundation L/D=0.7 on soil at different relative densities.

Figure 9 Stress-settlement relation for skirted foundation L/D=1 on soil at different relative densities.

Figure 10 Stress-settlement relation for skirted foundation L/D=1.5 on soil at different relative densities.
7.4. Variation of the bearing capacity ratio with skirt ratio

The bearing capacity ratio BCR is defined as the ratio of bearing capacity of skirted footing to the bearing capacity of ordinary footing at any given relative density of gypseous soil. The variation of the bearing capacity ratio (BCR) is plotted versus L/D ratio in Figure (13). The increase in length to diameter ratio of the skirted footing led to increase in BCR. However, the rate of increase in BCR with skirt ratio is not the same for footings embedded in gypseous soil of different relative densities. The increase in the BCR with length to diameter ratio of skirted footing is higher for footings embedded in gypseous soil with higher relative density. The results are summarized in Table (4). So it can be concluded that the improvement of bearing capacities a function of length to diameter ratio of skirted footing and relative density. From Figure (17), the improvement of BCR is 1.92 and 2.3 for relative density 55% and 70%, respectively.

Figure 11 Stress-settlement relation for skirted foundation L/D=2 on soil at different relative densities.

Figure 12 Stress-settlement relation for skirted foundation L/D=3 on soil at different relative densities.
Figure 13 Variation of the BCR with depth ratio for models on dry gypseous soil.

Table 4 Vertical failure stress ratio for models on dry soil.

<table>
<thead>
<tr>
<th>Skirt ratio</th>
<th>Vertical failure stress (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(D_r = 55% )</td>
</tr>
<tr>
<td>L/D= 0</td>
<td>221</td>
</tr>
<tr>
<td>L/D= 0.25</td>
<td>259</td>
</tr>
<tr>
<td>L/D= 0.5</td>
<td>313</td>
</tr>
<tr>
<td>L/D= 0.7</td>
<td>355</td>
</tr>
<tr>
<td>L/D= 1</td>
<td>394</td>
</tr>
<tr>
<td>L/D= 1.5</td>
<td>431</td>
</tr>
<tr>
<td>L/D= 2.0</td>
<td>496.5</td>
</tr>
<tr>
<td>L/D= 3.0</td>
<td>425</td>
</tr>
</tbody>
</table>

8. CONCLUSIONS

1. The presence of skirts improves the bearing capacity of the surface footing on gypseous soil. The amount of improvement increases with increasing the depth to diameter ratio of skirted footing as well as relative density.

2. In general, at greater L/D ratio, the lines of failure below the footing will intersect with the existence of skirted and its effect does not arrive to surface of soil.

3. In the special case when L/D = 3 in medium relative density, the bearing capacity is less than the bearing capacity of L/D = 2.

4. The improvement of bearing capacity is a function of length to diameter ratio of the skirted footing and relative density of soil, where it increases with increasing these factors.

REFERENCES


Experimental Study on Bearing Capacity of Skirted Foundations on Dry Gypseous Soil


