Enhancing the ability of the square footing to resist positive and negative eccentric-inclined loading using an inclined skirt

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Abstract. Laboratory model tests were performed to investigate the behavior of shallow and inclined skirted foundations placed on sandy soil with R.D%=30 and the extent of the impact of the positive and negative eccentric-inclined loading effect on them. To achieve the experimental tests it was used a box of (600*600)mm cross-sectional and 600mm in height and a square footing of (50*50)mm and 10mm in thickness attached to the skirt with Ds=0.5B and various an angle of (10°,20°,30°). The results showed that using skirts leads to a significant improvement in load-carrying capacity and decreased settlement in addition when the skirt angle increased, the ultimate load improved. load-carrying capacity decreased with increasing eccentricity and load inclination For load inclination (Beta) 15° when the eccentricity changed from e=0.15B to e=0.05B the load improvement percentages were (323.2% to 263%) and (214% to 220%) and settlement reduction factor was (83% to 78%) and (62% to 58%) for positive and negative eccentric-inclined loading, respectively also the result showed the effect of positive on the reduction of soil-bearing capacity is more than negative. Increasing eccentricity increases the improvement percentage for positive eccentric-inclined load and decreases for the case of negative eccentric-inclined load. Increased skirt angle will increase the Improvement factor (IR) When the skirt angle increased from 10° to 30° for an improved foundation with load angles of 5°, 10°, and 15° the improvement factor (IR) increased from (2.53, 2.51, 2.4) to (3.45, 3.65, 3.97) and (2.43, 2.58, 2.54) to (4, 4.63, 5.3) for both negative and positive eccentric-inclined load respectively and settlement reduction factor for load angle 15° and skirt angle increase from 10° to 30° were 34% and 27% for positive and negative eccentric-inclined load respectively. the (IR) for positive eccentric-inclined load is more than the negative eccentric-inclined load for all cases, in addition, the skirt angle of 30° showed a significant improvement in the improvement factor (IR).

Keywords: shallow foundation, sandy soil, skirted foundation, positive and negative eccentric-inclined loading, skirt inclination angle.

1. INTRODUCTION

Geotechnical engineering mostly deals with the problems of foundation settlement and soil carrying capacity [1,2]. Numerous methods for improving soil have been developed in recent years to enhance its characteristics [3]. However, due to the restrictions of the site circumstances, some of these technologies are too costly and cannot be used. It has been discovered that a skirt is an excellent alternative for improving the soil's carrying capacity and decreasing settlement in shallow foundations[4,5]. The skirt foundation may have one sidewall or more depending on design requirements and these sidewalls can be vertical or inclined under the footing, Skirt foundation creates a confining for soil [6–8]. skirted foundations can be made from concrete or steel walls[9].

Experimental tests have been done to study the effects of skirt location according to the load position, number, and length of the skirt on the performance of a rectangular skirted foundation under lateral load placed on sandy soil. the results were the lateral bearing capacity increased with increasing skirt length and skirt number which the optimum may be two skirts also the location of the skirt has a significant effect corresponding to load direction[4].

An experimental laboratory test was carried out to study the performance of rectangular skirted footing placed on sandy soil under vertical loads. The result showed that an increase in the skirt length will improve load-carrying capacity and the highest improvement in bearing capacity was 262% as compared with the unskirted foundation and the improvement is more effective for low relative density. The improvement was linear with foundation width for both skirted and unskirted foundations[10].

twelve experimental trials were carried out on steel circular footings of varying diameters and skirt lengths. Furthermore, the soil employed in this experiment was sandy soil with a constant moisture content and compaction process. The laboratory experiments showed that skirts are completely successful at increasing ultimate carrying capacity because they can extend their length, which increases ultimate carrying capacity approximately (4.70) times in specific experimental conditions. Skirts could also help to decrease settlement[11].

small scale model of the foundation was performed to examine the behaviors of circular-skirted footing placed on sandy soil under vertical loads and study the effect of (relative density, foundation diameter, roughness surface of model, and depth of skirt) on load-carrying capacity and foundation settlement which will compare with foundation without a skirt. The result showed that increasing the skirt's depth and surface roughness of the skirt side and a decrease in relative density will lead to an increase in bearing capacity and reduce foundation settlement. The bearing capacity improved up to five times and the settlement was reduced by 8% from footing without a skirt[12].

The test model was used to study the effect of (skirt depth, Relative-density, and type of skirted footing) on the sand. the skirt was varied types such as plus shape and a double box shape. The outcomes indicated that the bearing capacity and behavior increase due to the geometry of the footing and skirt. Moreover, the lowest improvement was approximately 26% by using square footing with (Ds=0.25B, Dr=60%) unlike the maximum improvement was 364% by using double box footing with(Ds=1.5B, Dr=30%[13].

an experimental test was performed to investigate the effect of (various combination types of skirt footing, and loose and dense conditions of sandy soil. The outcomes have demonstrated that more parts of the skirt improve the ultimate load. The bearing capacity decrease under high load eccentricity for a strip foundation[14].

A numerical investigation was carried out using the FEM plaxis3D program (different skirt lengths and skirt angles, eccentric load), and it was discovered that increasing the skirt length improves bearing capacity and decreases settlement due to an increase in the displaced soil volume, which generates an increase in soil pressure, and increasing the eccentricity reduce the load-carrying capacity and increases settlement. On the skirt side, the horizontal soil reaction assists in preventing the foundation from sliding. Because of the horizontal soil reaction generated on the skirt side, the angle of the skirt has a strong effect on the bearing capacity of the soil[15].

A numerical test was carried out to study the effects of skirt length on the lateral bearing capacity for skirted foundation rest on sandy soil. lateral bearing-capacity increase with increasing skirt length and when the skirt length increases the failure mode change from sliding mode to rotational. the failure mode of footing without a skirt is sliding failure[16].

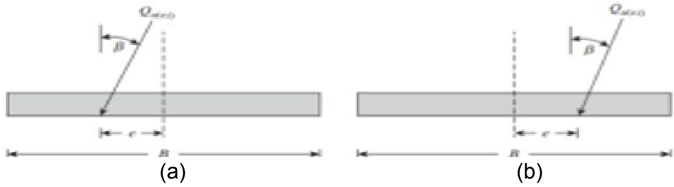
an experimental test was carried out to find out the behavior of square footing with a skirt compared with a square surface footing placed on dry gypseous soil of (R.D)= 33% and study the effect of skirt length. The result shows that a skirted foundation increases load-carrying capacity and reduces settlement. Using a skirt length of about 1.5B leads to improving the bearing capacity by up to 190% and reducing settlement by up to 186%. Under eccentric load e=8mm with skirt length =1.5mm the bearing capacity increased by 120% and when e=17mm and skirt length =1.5 the settlement increased up to 105%[17].

Finite element software (ABAQUS) was carried out on the skirted foundation to investigate the effect of (skirt length, internal skirt, and inclination of skirt) under vertical load on sandy soil. The results show that when increasing skirt length the bearing capacity increases and reduces the settlement. bearing capacity raised to 2 times from surface footing and settlement decreased by 60% while using skirt length=1.5B(B=foundation width). Furthermore, providing additional internal skirts leads to reducing the value of both settlement and bearing capacity slightly. Bearing capacity was raised by 1.8% as compared to surface footing and settlement decreased by 78% as compared to surface footing when the inclination angle of the skirt is 25 degrees[18].

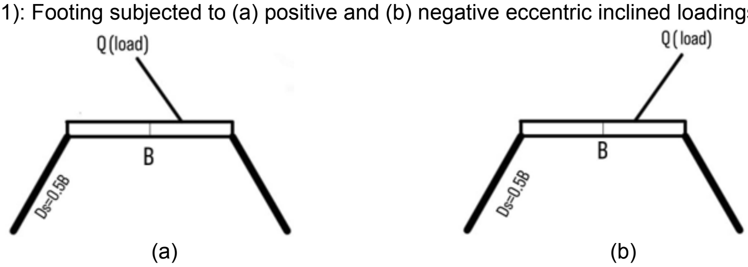
A numerical test using the finite element method was carried out to investigate the behavior of an octagonal mat foundation with and without a skirt under various eccentric load conditions. The results showed that differential settlement reduces when the length of the skirt increase and the reduction value of the settlement in a range of (15-60%). The settlement due to vertical load does not affect by skirt inclusion length up to (3)m. Increasing skirt length leads to a decrease in foundation rotation angle by (50-75%). For (6)m skirt length and (16)m foundation diameter under a maximum eccentricity of 4.01the reduction of rotation angle was observed at 47%[19].

A numerical test using FEM (GEO STUDIO) was carried out to study the effect of soil infiltration on circular-skirted footing placed on gypseous soil. The result showed that bearing capacity and settlement improved with increasing skirt length and the settlement under footing was the same and not differential[20].

Examining the above literature shows that using skirts leads to improve load-carrying capacity and reduce settlement under different parameters, in addition, observed that positive and negative eccentric-inclined loading subjected to inclined skirts has not been used. In this paper, a small experimental model was used to evaluate the performance of a square footing resting on loose sandy soil to resist positive and negative eccentric-inclined loading as shown in Fig.(1) and Fig. (2) using an inclined skirt with a skirt angle (10, 20, 30) and Ds=0.5B.



Figure(1): Footing subjected to (a) positive and (b) negative eccentric inclined loadings



Figure(2): footing with skirt subjected to (a) negative (b) positive eccentric-inclined loadings.

2. Testing Techniques and Materials Used

2.1 Testing Apparatus

The testing apparatus is made up of three major components: the sandbox, the loading mechanism, and the footing and skirt model. The next preceding sections provide a full description of each component.

(a) The Sand Container

The sand container is a steel box of dimensions (600×600×600 mm depth), made of a steel plate of 3 mm thickness, the side of the box was made from glass with 10mm thickness as shown in Fig.(3). The dimensions of the box were chosen to be sufficient to prevent the influence of boundary conditions on the base [21]. The internal faces of the box were covered with polyethylene sheets, in order to reduce the slight friction which might be developed between the box surface and the soil.

Figure(3): The sand container

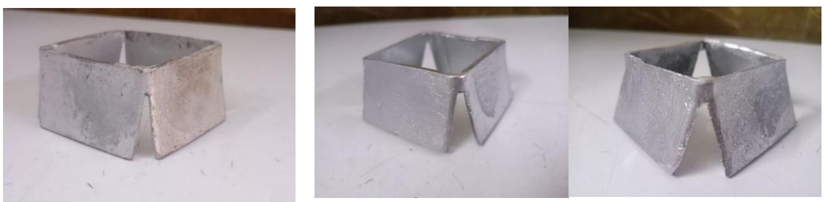
(b) The Loading System

A loading steel frame with an arch to control the load inclination was used to carry out the axial loading on the footing and an electrical jack with an electrical transformer has been added to control the speed of loading. a load cell SC516C-1 ton was connected to the electrical jack for measuring the applied load on the footing, 3 linear variable displacements (LVDT) were used two of them were placed vertically on the right and left of the footing to measure the settlement, and the third one was placed horizontally to measure the horizontal displacement, load cell, and LVDT were connected to the data logger.

(c) The Model of Footing and Skirt

A square footing has dimensions of (50mm*50mm) and a thickness of 10mm shown in Fig(4), small holes were created on the surface of the footing to ensure that the loading arm does not change its location as shown in Fig(4). A skirt with 4 sides was used with a dimension of 50mm*50mm and depth of (0.5B) and a thickness of 5mm, The skirt angles were used (10˚, 20˚, 30˚) as shown in Fig(5). Footing contains a small piece of iron welded over the footing to connect the footing with a skirt.

Figure(4): Footing model used.

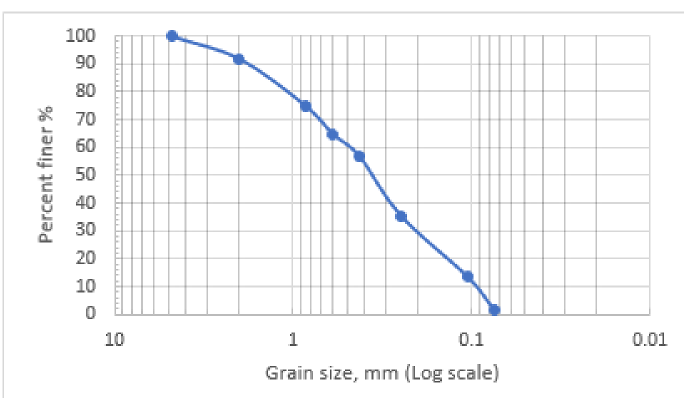


(10°) (20°) (30°)

Figure(5): Skirt models used

2.2 SANDY SOIL

Locally sandy soil from the governorate of Karbala located in the southwest of Baghdad was collected washed and dried. The sand passing from the sieve(No.4) was used. The grain size is analyzed according to the ASTM (D422-63). According to the grain-size distribution curve shown in Fig (6) the sand is classified as poorly. Laboratory tests were carried out on the sand to get some other properties and their values are listed in Table (1):



Figure(6): Grain Size Distribution of The Sandy Soil.

Table(1): physical properties of used sand.

No.	Property index	value	Specifications
1	Specific gravity (Gs)	2.664	ASTM D-854-92[26]
2	D10(mm)	0.1	ASTM D-6913/D6913M-17 [22]
3	D30(mm)	0.214	
4	D60(mm)	0.494	
5	Coefficient of uniformity (Cu)	5.117	
6	Coefficient of curvature (Cc)	0.959	
7	Maximum dry unit weight (KN/m^3)	18.3	ASTM D-4253 and D-4254 [25] [27]
8	Minimum dry unit weight (KN/m^3)	15.6	
9	Dry unit weight in test (KN/m^3) at R.D=30%	16.32	
10	Maximum void ratio	0.66	
11	Minimum void ratio	0.415	
12	Relative density (R.D)%	30	ASTM D-2049-64 [24]
13	The angle of interior friction Ø at R.D=30%	32.3°	ASTM D-3080-90 [23]
14	Soil classification (USCS)	Poorly graded sand (SP)	Unified soil classification system

2.3 Test Procedure

A laboratory model test was performed in a frame loading with a box of dimension (600*600)mm and height of 600mm and the load cell was attached to the loading arm. A square footing of (50*50)mm with 10 mm thickness and skirts of (50*50)mm with 5 mm thickness and d/B=0.5 in addition to skirt angle (alpha) (10°, 20°, 30°) were used in the test. The raining technique was used to prepare the sand inside the box, for obtaining a relative density R.D%=30 the washed dried sand that passed from the sieve (No.4) pour into the box from a constant height of 12 cm which was chosen after many trials to find the require relative-density 30%, the box was divided to 6 layers of 10 cm by marking the glass side of the box. An aluminum plate is used to level the surface of each layer carefully level to ensure obtain the required relative density. During the preparation of soil inside the box, the box is filled to the required height depending on the foundation type, for shallow surface footing the box is filled and leveled top surface of the soil then placed the square footing on the center of a leveled surface as shown in Fig (7), for skirted footing the box is filled with soil to a specific height equal a height of skirt then level the surface and place the skirt on center as shown in Fig(8) after that keep the poring soil to fill the box and inside of skirt then level the surface and place a footing inside the skirt. The loading is applied gradually and settlement corresponds to the applied load, and displacement was recorded.

Figure(7): Preparation of the test box for surface footing.

Figure(8): Preparation of the test box for a skirted foundation.

3. Results and Discussions

A group of 54 experimental tests was conducted to find out the behavior of the square shallow foundation and skirted foundation. Shallow square footing with a dimension of (50*50)mm and skirted foundation placed on the loose sandy soil of (R.D)=30% subjected to positive and negative eccentric-inclined loads. Several parameters have been studied such as load inclination (Beta) (5°, 10°, 15°), eccentricity ratio (0.05, 0.1, 0.15) of foundation width in addition the length of the skirt was Ds=0.5B (B= width of foundation) with various skirt angle (Alpha) (10°, 20°, 30°). For all these test groups, the failure criteria that was adopted as mentioned by Terzaghi is a settlement corresponding to 10% of footing width.

3.1 Load Settlement Behavior

18 experimental tests of the shallow foundation were performed as a reference to compare with the skirt foundation subjected to positive and negative eccentric-inclined loads. Also, these same loads were subjected to the skirt foundation for 36 tests were conducted to compare it with the shallow foundation. Several curves were drawn for the loading-settlement curve to observe the behavior of the foundation before and after the improvement under the same loading conditions. The figures from (9) to (14) represent the effect of two cases of negative and positive eccentric-inclined loading on both the unimproved and improved foundations with inclined skirts (Alpha) 20° drawn together for the comparing purpose and various cases of eccentricities.

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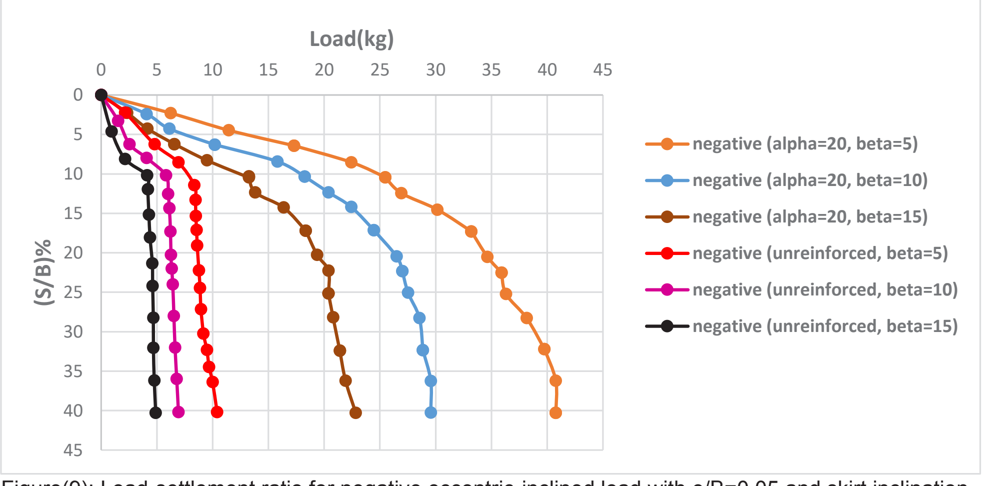
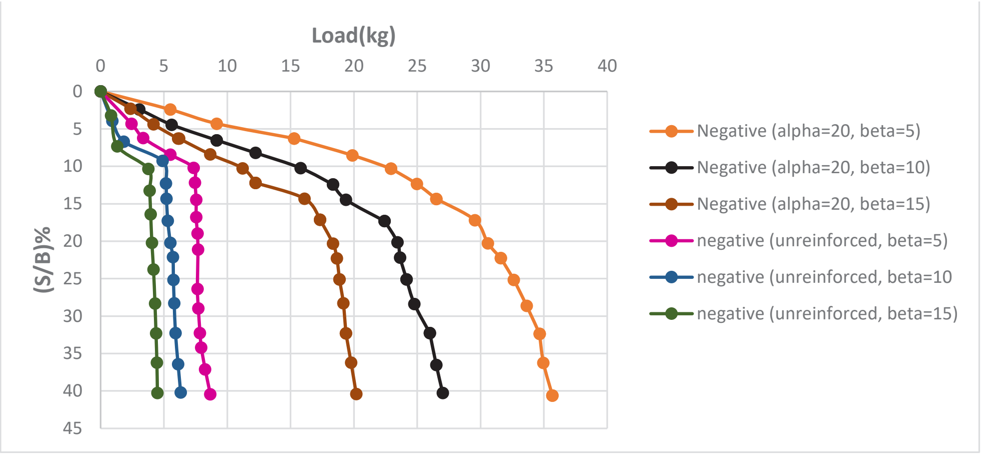
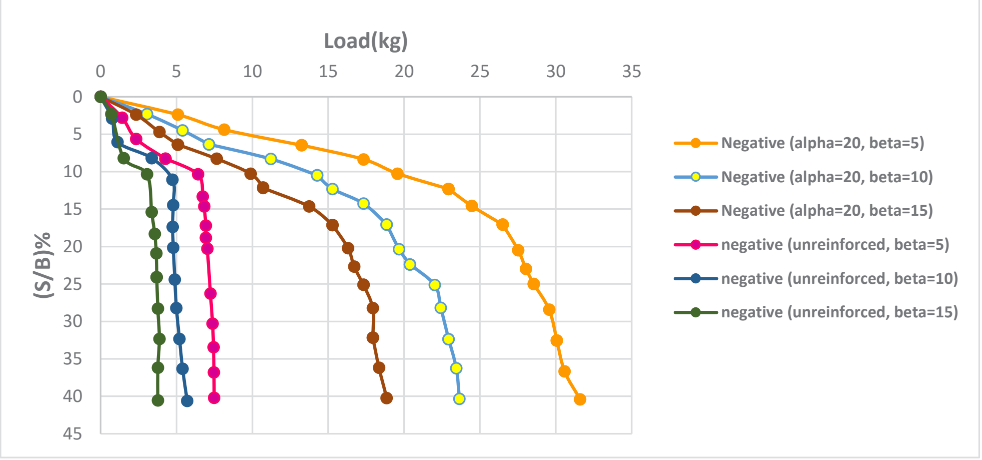


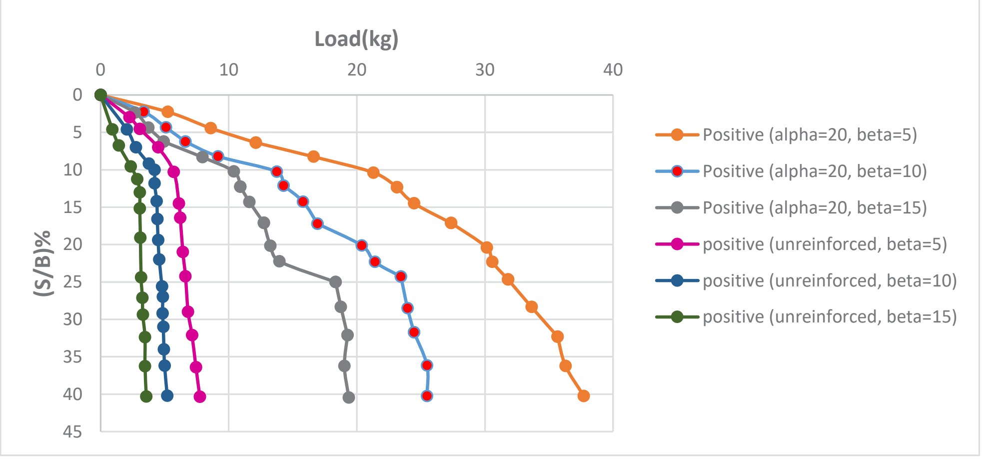
Figure(9): Load-settlement ratio for negative eccentric-inclined load with e/B=0.05 and skirt inclination (Alpha) 20°.



Figure(10): Load-settlement ratio for negative eccentric-inclined load with e/B=0.1 and skirt inclination (Alpha) 20°.



Figure(11): Load-settlement ratio for negative eccentric-inclined load with e/B=0.15 and skirt inclination (Alpha) 20°.



Figure(12): Load-settlement ratio for positive eccentric-inclined load with e/B=0.05 and skirt inclination (Alpha) 20°.

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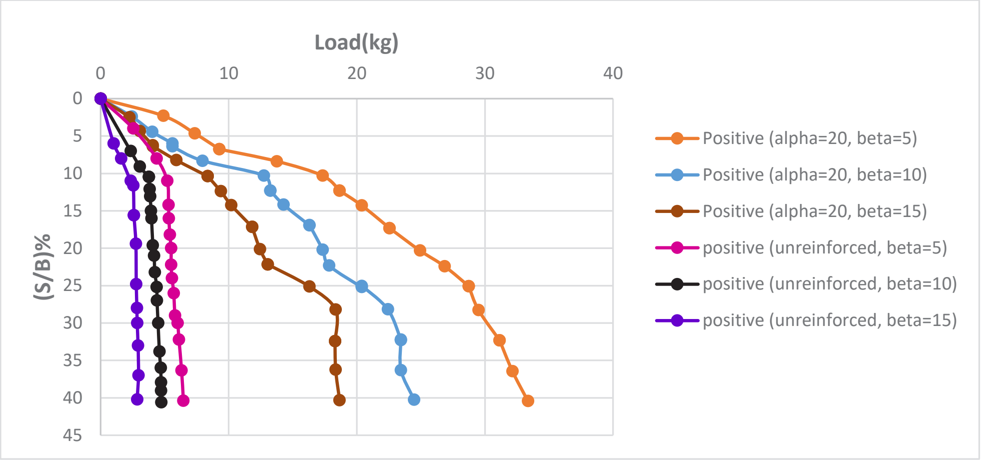
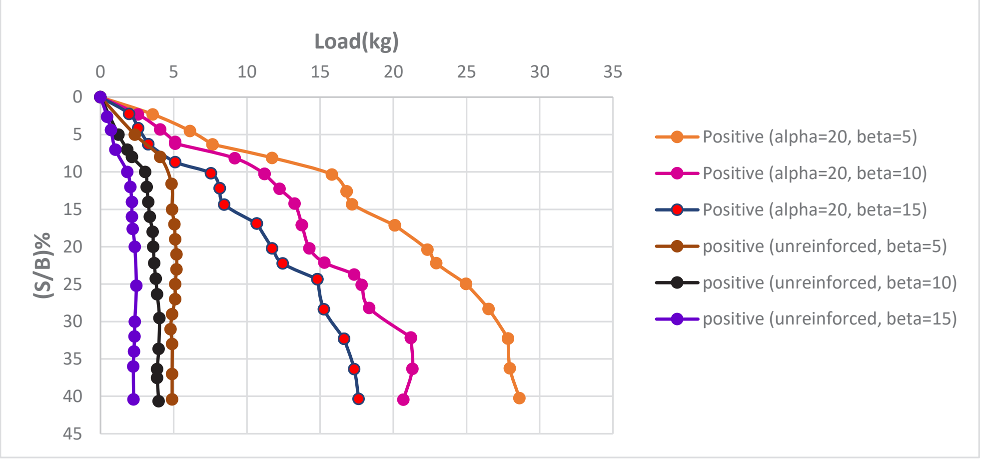


Figure(13): Load-settlement ratio for positive eccentric-inclined load with e/B=0.1 and skirt inclination (Alpha) 20°.



Figure(14): Load-settlement ratio for positive eccentric-inclined load with e/B=0.15 and skirt inclination (Alpha) 20°

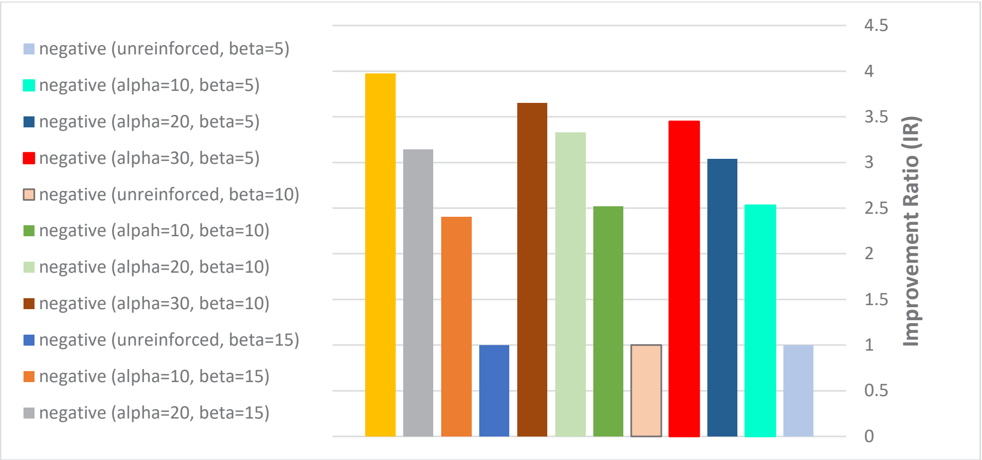
The results are generally shown that employing skirts improved the load-carrying capacity and decreased settlement for all loading cases because the skirts work to confine the soil below the footing and lead to making the foundation acts as a single part to transfer loads to great depths. In addition, the load-carrying capacity of unimproved and improved foundation with skirt is reduced with increasing eccentricity and loading angle for all cases which agrees with [5,8,28–31].

Analysis of experimental results showed that the effect of positive eccentric-inclined loading on the reduction of soil-bearing capacity is more than negative eccentric-inclined loading for all cases due to the fact that the applied loading affects away from the center of the foundation and this agrees with the result of [29,32].

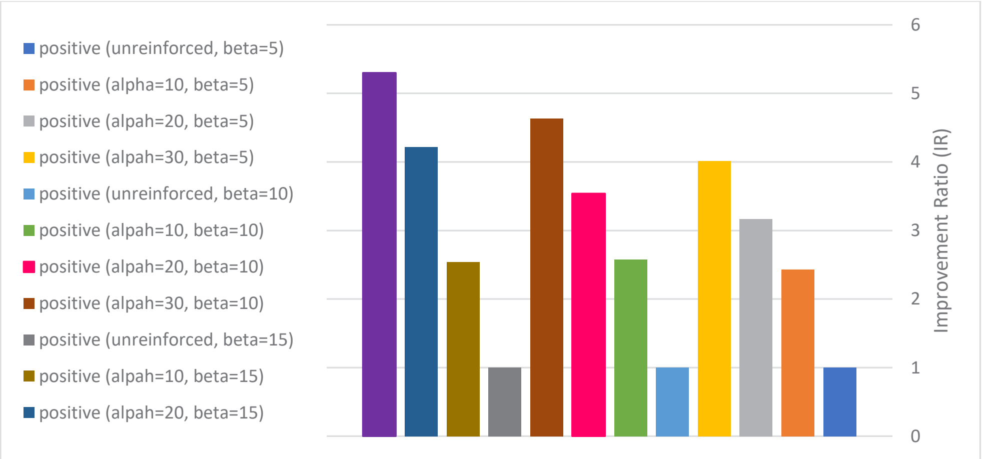
The load-carrying improvement percentage [(Pr/P-1) *100] (where Pr and P are the maximum loads for improved and unimproved sand, respectively) For load inclination (Beta) 15° when the eccentricity changed from e=0.15B to e=0.05B the load improvement percentages were (323.2% to 263%) and (214% to 220%) and settlement reduction factor were (83% to 78%) and (62% to 58%) for positive and negative eccentric-inclined loading, respectively, and have two results, the first one when eccentricity increased the improvement percentage increase for positive eccentric-inclined load, and decrease for the case of negative eccentric-inclined load. The second result showed that the improvement percentage for positive eccentric-inclined load is more than the negative eccentric-inclined load.

3.2 Effect of Skirt Angle

To analyze the effect of increasing skirt angle (alpha) on the behavior of the foundation placed on sandy soil, skirts with various angles (10°,20°,30°) and Ds=0.5B were used. A bar chart expressed by improvement factor (IR) has been used as shown in Fig (15) and Fig(16) To assess the effect of skirt angle. It must be noted that IR=1 for unimproved footing.



Figure(15): Variation of improvement ratio with skirt angle (alpha) under negative eccentric-inclined load with e/B=0.15.



Fig(16): Variation of improvement ratio with skirt angle (alpha) under positive eccentric-inclined load with e/B=0.15.

From the result above the increasing skirt, angle leads to an increased improvement factor (IR).when the skirt angle increased, the ultimate load improved due to a contact area being created between the inclined skirt angle and soil and this agrees with the result of [8,15,18]. The improvement factor (IR) for positive eccentric-inclined loading was more than negative. When the skirt angle increased from 10° to 30° for an improved foundation with load angles of 5°, 10°, and 15° the improvement factor (IR) increased from (2.53, 2.51, 2.4) to (3.45, 3.65, 3.97) and (2.43, 2.58, 2.54) to (4, 4.63, 5.3) for both negative and positive eccentric-inclined load respectively and settlement reduction factor for load angle 15° and skirt angle increase from 10° to 30° were 34% and 27% for positive and negative eccentric-inclined load respectively. From the results above when the loading inclination increased the improvement factor increased for both negative and positive eccentric-inclined loading. The skirt angle of 30° showed a significant improvement in the improvement factor (IR).

4. Conclusions

1- Loads-carrying capacity decreased and settlement increased with increased both eccentricity and loading angle for all cases, for load inclination (Beta) 15° when the eccentricity changed from e=0.15B to e=0.05B the load improvement percentages were (323.2% to 263%) and (214% to 220%) and settlement reduction factor were (83% to 78%) and (62% to 58%) for positive and negative eccentric-inclined loading, respectively.

2- The effect of positive eccentric-inclined load on the reduction of soil-bearing capacity and increasing settlement is more than negative eccentric-inclined loading for all cases.
3- The improvement percentage for the positive eccentric-inclined load is more than the negative eccentric-inclined load.
4- Increasing eccentricity increases the improvement percentage for positive eccentric-inclined load, and decreases for the case of negative eccentric-inclined load.
5- Increased skirt angle will increase the Improvement factor (IR) and the (IR) for positive eccentric-inclined load is more than the negative eccentric-inclined load for all cases, When the skirt angle increased from 10° to 30° for an improved foundation with load angles of 5°, 10°, and 15° the improvement factor (IR) increased from (2.53, 2.51, 2.4) to (3.45, 3.65, 3.97) and (2.43, 2.58, 2.54) to (4, 4.63, 5.3) for both negative and positive eccentric-inclined load respectively and settlement reduction factor for load angle 15° and skirt angle increase from 10° to 30° were 34% and 27% for positive and negative eccentric-inclined load respectively.
6- The skirt angle of 30° showed a significant improvement in the improvement factor (IR).

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