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Response of Skirted Foundations Resting on Dry Medium Dense Sand

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Abstract

Experimental model tests were carried out to study the response of skirted foundation resting on dry sand. The experiments were performed in a large soil container (1000 × 1000 mm in cross section and 800 mm in height). Skirts with three different lengths (L) varied from 0.5D to 1.5D was attached to the edge of shallow circular foundations having three different diameters (D=60, 90 and 120 mm). Different parameters have been studied; these parameters involve skirt length, foundation size and skirt conditions. Skirts with open end and closed end were used. The relative density was kept constant and equals to 60%. The case of foundation without skirt (L=0) was initially tested and set as a reference for comparison purpose. From the results of experimental tests, it was found that the skirt modifies the load-settlement behaviour, increasing the load carrying capacity and reducing the foundation settlement. The results also indicate that load carrying capacity of skirted foundation increases with increase skirt length as well as foundation size. The results show that using skirt with closed end brought a considerable increase in load carrying capacity than that of open end.

Keywords: Medium Dense Sand; Skirt; Load Carrying Capacity; Circular Foundation; Physical Model Tests; Dry.

1. Introduction

The poor ground conditions like loose to medium dense sand pose the problem of low bearing capacity and large settlement of foundation resting on it under relatively lesser loads, therefore it became necessary to develop and apply various methods of soil improvement, for example soil reinforcement, deep compaction, grouting … etc. Some of these methods may be expensive, restricted by the site conditions and difficult to apply. Thus geotechnical engineers are trying to find out alternative methods to enhance bearing capacity and reduce settlement of the structures. The use of skirts is one of the most alternative methods for improving soil capacity. Skirted foundation have proven to be competitive alternatives to more traditional foundation solutions like piles in various types of soils due to their economic benefits which lead to cost saving through reduction in materials and in time required for installation. It is also utilized as an alternative to deep foundation in soil has low strength at its surface.

The term skirted foundations is utilized to define shallow foundations with vertical or inclined thin structural elements fixed along its edges, called “skirt” to increase the bearing capacity and/or provide scour protection whichpenetrate the soil and surround one or more sides of the soil underneath the foundation and thus constrain its lateral movement.

When using skirts an enclosure is formed in which the soil mass is restrict and work as a soil plug to transfer superstructure loads to depths where the soil is stronger, thereby increasing its bearing capacity. Skirts may be used with new or existing foundations of circular, rectangular and square shape. It can be of any shape but generally the shape of

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the skirt is kept same as the foundation shape.

These types of foundations are widely used in designing offshore foundations where structures have to sustain large loads and moments produced by environmental conditions. Skirts fixed on the circumference of foundations have been used for a long period to increase the effective depth of foundations in marine and other cases where water scours may be a major issue, due to their stability features. This method does not need excavation of soil therefore it cannot be restricted by the presence of water table.

In this study, a total of twenty one experimental tests are carried out to predict the behavior of skirted foundations under vertical loads found on sand deposit using a physical model. The main objectives of the experimental tests are to evaluate improvement values in load carrying capacity and reduction values in foundation settlement due to the application of skirt, to study the effect of skirt length and the effect of foundation size on the response of skirted foundation. The effect of open end skirt and closed end skirt is also investigated.

2. Literature Review

El Wakil (2010) [1] explored the performance of skirted foundation subjected to lateral loads by performing a laboratory tests on circular skirted foundation. He studied the influence of relative density of sand and length of skirt. The results indicated that there was a remarkable increase in the ultimate horizontal bearing capacity of shallow foundations because of using the skirts. He concluded that the skirt changed the failure mode of foundations from sliding to rotational mechanism.

Pusadkar and Bhatkar [2] (2013) used the finite element software PLAXIS 2D to study the performance of one side skirted foundation and two sides skirted foundation. They investigate the effect of raft foundation sizes and depths of skirt. They found that the vertical skirt has a significant influence in improving the bearing capacity of raft foundation. They observed that for two sides skirted foundation when increasing depth of skirts with varying raft size the settlement decreases and bearing capacity increases. While for one side skirted foundation there was increase in bearing capacity as well as settlement.

Pachauria et al. (2014) [3] carried out a laboratory model tests to study the effect of foundation diameter on load carrying capacity of skirted sand. Foundations with four different diameters were used on loose sand having embedded skirt inside. The skirts of four different diameters were inserted in the sand. It was seen that increasing the diameter of foundation with the same diameter of skirt the load carrying capacity increases, and when increasing the diameter of skirt with constant diameter of foundation the load carrying capacity also increases.

Chandrawanshi et al. (2014) [4] preformed model tests on circular foundation resting on medium dense sand with and without skirts of different diameters and heights. They studied the effect of skirt diameter on bearing capacity ratio in sand and effect of skirt height on bearing capacity ratio of skirted foundation in sand. They found that the bearing pressure corresponding to 10% S/D ratio (i.e. 5 mm settlement), remarkably increases when using skirts to confine the sand. For skirts with small diameters, the influence was small and reaches an optimum value for a fixed skirt diameter with respect to pile diameter and then this phenomenon loses its significance as diameter of skirt increases.

Momeni et al. (2015) [5] made an experimental and numerical study to look at the bearing capacity of a new precast thin-walled spread foundation known as an IBS foundation in loose and dense sands. The experimental results showed an enhancement in the bearing capacity by a factor of almost 2 when the thin-walled foundation is used instead of a simple foundation. They investigated the influence of sand the relative density on the bearing capacity for IBS foundations. It was found that changing the relative density from 30 to 75% improves the bearing capacity of the IBS foundation by 3.6 times. This ratio was 3.7 when the bearing capacities of IBS foundations in loose and dense sands were obtained numerically by using FE software, Abaqus.

Thakare and Shukla (2016) [6] Performed lateral loading tests to shed the lights on the performance of rectangular skirted foundations. They investigated the effect of embedment depth of skirt to foundation width (D/B) ratio, number of skirts attached to foundation and different load inclinations. It was found that increase in the number of skirts and D/B ratio increased the ultimate lateral load carrying capacity of foundations significantly. Locations of skirts with respect to loading direction also have a significant effect on the ultimate lateral load capacity of shallow footings. Load carrying capacity of footing increases with increase in inclination of load in plan.

Khatri et al. (2017) [7] investigated the pressure-settlement behavior and bearing capacity of square and rectangular skirted foundation resting on sand and subjected to a vertical load through laboratory experimental tests. They used a foundation with a width of 50 mm and 60 mm and length/width ratio of 1 and 2. Sand with different relative density was used (Dr= 30 %, 50 %, 70 %, and 87 %). The depth of skirt was varied from 0.25 B to 1.0 B. The results revealed that, the use of structural skirt improves the bearing capacity of foundation significantly. The improvement in bearing capacity was observed almost linearly proportional to the depth of skirt. The improvement in bearing capacity of skirted foundations over foundations without skirt was observed in the range of 33.3% to 68.5%, 68.9% to 127% and 146.7%

to 262% for a skirt depth of 0.25 B, 0.50 B and 1.0 B respectively. The skirted foundations were found more effective in sand of relative density 30% and 50% than that of relative density 70% and 87%. The bearing capacity was found to increase linearly with foundation width for foundations with and without skirts.

3. Experimental Tests and Materials Used

3.1. Sand

Locally available sand was taken for this experimental investigation. Prior to testing, the sand was washed and dried then it was sieved through 2 mm sieve. Figure 1 displays the particle size distribution of the used sand. The standard tests conducted on the sand in the laboratory were sieve analysis test, specific gravity test, direct shear test and minimum and maximum dry unit weight tests. The details of geotechnical and engineering properties of the sand are listed in Table 1. The sand is classified as SP (i.e. poorly graded sand) based on the unified soil classification system (USCS). Classification of sand based on relative density is medium dense sand.

Figure 1. Grain size distribution of the sand

Table 1. Physical properties of the sand used

Property	Value
D_{10}	0.14 mm
D_{30}	0.23 mm
D_{60}	0.41 mm
Coefficient of Uniformity (C_u)	2.93
Coefficient of Curvature (C_c)	0.92
Specific Gravity (G_s)	2.64
Angel of Internal Friction (Ø)	34°
Max. Dry Unit Weight (γ_{dmax})	17.5 kN/m³
Min. Dry Unit Weight (γ_{dmin})	14.2 kN/m³
Dry Unit Weight in Test (γ_d)	16.012 kN/m³
Relative Density of Sand During Test (D_r)	60 %

3.2. Foundation Models

Circular foundation models of different sizes (D= 60, 90 and 120 mm) with a thickness 20 mm were used. The foundation models consist of two parts, the upper part of 10 mm thick was made of aluminum, while the lower part of 10 mm thick was made of concrete with a mix ratio 1:1.5:3 for the purpose of simulating the reality where the foundations are made of concrete rest on soils, as shown in Figure 2.

Figure 2. Foundation models

3.3. Skirts

Aluminium cylinders open at both ends were cut in lengths of 0.5D, D and 1.5D to act as a skirt in the present study. These skirts were used to confine the sand laterally under the circular foundation model. The skirts have inner diameters of (60, 90 and 120) mm for foundation diameter equal to (60, 90 and 120) mm, respectively. The thickness of all skirts was constant and equal to 5 mm, as shown in Figure 3. The foundation was placed on the top of the skirt and they were attached to the foundation by bolts. For the case of skirts with closed end, caps were provided at its bottom which is rigidly attached to the skirt by bolts. The inner and outer surface of the skirts was smooth to prevent the effect of the interface friction between the sand and the skirts.

Figure 3. Skirts

3.4. Test Set Up

The test set up contains a square test tank as a soil container, circular foundation models, sand raining apparatus and loading system. The test tank used in this study was 1000 × 1000 mm in plan and 800 mm in deep with 10 mm sides and base thicknesses. The tank was made of glass; the purpose of using glass is to allow better observation of soil homogeneity also a reference markers were used in the front side of the tank to help with the formation of the required sand model. The dimensions of the box were large enough to overcome the boundary condition effects on the foundations response [8], whereas the width of the soil bin was about 8 times the diameter of the largest foundation and the depth under the longest skirt was 3.5 times the diameter of the largest foundation.

The loading system consists of a manual press which is used to apply the load. The maximum load that can be applied through the manual press is about 1 ton, a tension/compression load cell "SEWHA, Korea" S-beam model SS300 type made of stainless steel – LS300 and of a maximum capacity 1 ton is utilized to measure the loads, for displaying the magnitude of the load, a digital weighing indicator "SEWHA, Korea" SI 4010 model of 50 gm input sensitivity is used which is locally calibrated. These were supported by a movable loading frame mounted of a horizontal steel beam supported on the two columns. A base made of steel was used to support the weight of test tank and the loading system.

To ensure homogeneity of sand formation and reconstruct the sand at the specified relative density, sand raining technique was used in which the sand is permitted to rain through air at a controlled rate of discharge and specific height of pour to get uniform densities.

The use of this method for obtaining the required relative density has been reported by many researchers [9-11]. By using the raining technique, any density within the maximum/minimum density range can be achieved by controlling the intensity and the height of fall of the sand [12-14].

In the current study, A sand raining apparatus was designed consist of a moveable steel tank has a trapezoidal shape ending with an inclined funnel used as a hopper to fall the sand from different elevations through a lifting system which was designed to move the rain box vertically.

To start or stop deposition of the sand, a simple gate was prepared in the outlet of the funnel. A sliding system was provided to ease the horizontal movement of the hopper. A piece of mesh (diameter of the aperture is 10 mm) was put in the outlet of the funnel to reduce the impact of the particles [15]. Figure 4 shows the experimental setup used to preform the tests.

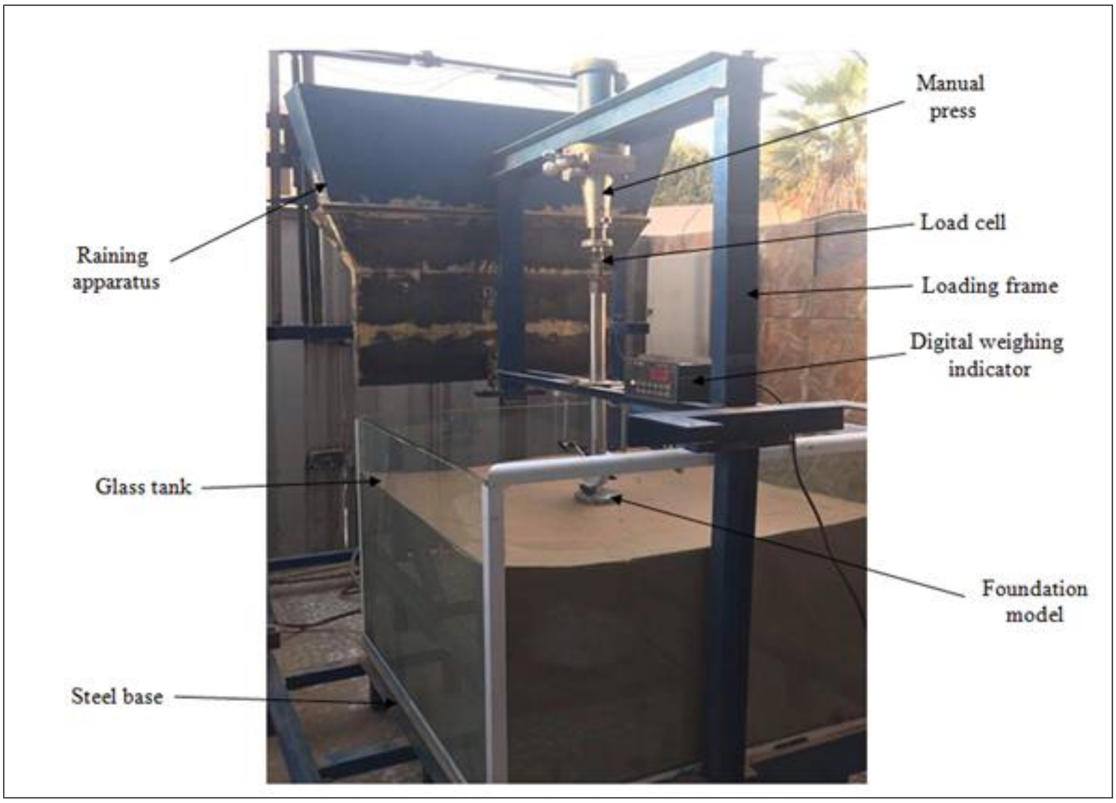

Figure 4. Test Set up

3.5. Preparation of Sand Bed

Raining method was utilized to fill the box with sand to the required level. For getting a uniform sand layer with a specific density, a raining device was designed, as outlined above. The flow rate of sand and height of pour affect the sand density in the raining technique [16].

Before depositing the sand in the tank, the raining system was calibrated by performing a series of trials with different dropping heights (40 mm, 50 mm and 60 mm). These trials carried out to check and control the uniformity of the sand bed.

Three trials were performed. In each one, small containers with known volumes were placed in various parts of the tank used to collect the samples for checking the density. After pouring the sand, each container was accurately taken and the density of the specimen was calculated. It was observed that the density of sand increases when the height of pouring increases.

In this study, the required level proportional to achieve the desired density of 60% was 430 mm. The relative density was kept constant at 60% in all tests to study this phenomenon for medium dense sand. When the raining box was filled with sand and the adequate level of pour was selected, the soil was dropped into the testing tank by a repeated horizontal movement of the raining box which was manually controlled. The sand bed was prepared in six layers of 100 mm constant height of each layer to get the required height of 600 mm measured from the bottom of the tank.

3.6. Test Procedure

The test tank was placed on the steel base and filled with sand by raining technique for getting a uniform particular relative density throughout the depth. Enough sand height was required within the test box to omit any effect of the box rigid bottom on the foundation response. After filling the tank with a controlled density, the rain box was removed and the sand surface was levelled gently by using straight plate of steel.

Several loading tests were carried out on different sizes of foundation of diameter (60, 90 and 120) mm placed centrally in the tank for application of load at various cases.

In each test, the foundation was loaded incrementally until the failure occurred. The vertical load was transmitted axially to the foundation through the manual press. The load was read from the digital weighing indicator connected to the load cell. Each load increment was maintained constant until the settlement was stabilized.

Initially, the foundation without skirts was tested. It was positioned carefully on the surface of pre-placed sand.

For foundations with skirts, the skirt was first pressed gently and vertically by hand into the sand followed by centring foundation model on surface of the sand.

Different skirt heights were selected and equal to 0.5D, D and 1.5D. The skirts were rigidly fixed to the foundation model using four bolts so that both will act as a single unit. The procedure described above was used for open end skirted foundations. For closed end skirted foundations, after filling the tank with sand to a defined position (i.e. height of the sand – height of closed end skirt) the closed end skirt was placed on the sand surface. After that, the raining of sand was continued to fill the tank.

When the required level of sand was reached (at the base of the foundation model), the sand raining was stopped and the raining box was removed.

Care was taken in placing the foundation models and installation the skirts in such a way that minimizing the change in the relative density and no disturbance occurred before loading to have the same density as that for foundation without skirts.

The average vertical settlement was measured by using two dial gauges of 0.01 mm accuracy and a range of 50 mm attached vertically at two different locations on surface of the foundation. A magnetic holder was used to fix the dial gauge on the loading frame.

It should be mentioned that, after the end of each test the sand was removed to a depth equal to 2.5D measured from the base of foundations without skirt and for foundations with skirt the depth 2.5D was measured from the bottom tip of skirt, then the raining was repeated again to start the next test.

4. Results and Dissuasion

Twenty one experimental model tests were carried out on isolated circular foundations (60 mm, 90 mm and 120 mm in diameter) with two types of skirts (open end and closed end) to investigate the behaviour of skirted foundations resting on dry clean sand. The soil bed was prepared at a relative density of 60% (i.e. medium dense sand) by using raining technique, as mentioned above.

4.1. Load-Settlement Behaviour

The load-settlement relationships and the ultimate load of foundations with and without skirts were obtained. Three tests were carried out on foundation without skirt as a reference test for comparison purposes.

For all model tests, load carrying capacity value (the ultimate load) is taken as the load corresponding to a limited settlement that equals to 10% of foundation diameter as proposed by Terzaghi (1943). Figures 5, 6 and 7 display the variation of load with foundation settlement for foundation with open end skirts.

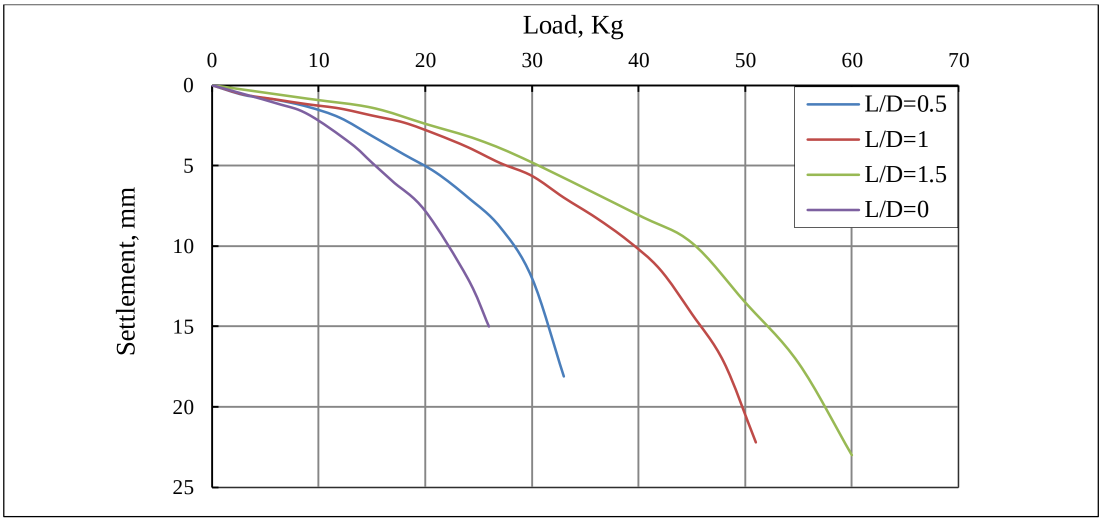

Figure 5. Load vs. foundation settlement relationship for foundation 60 mm in diameter at different skirt lengths

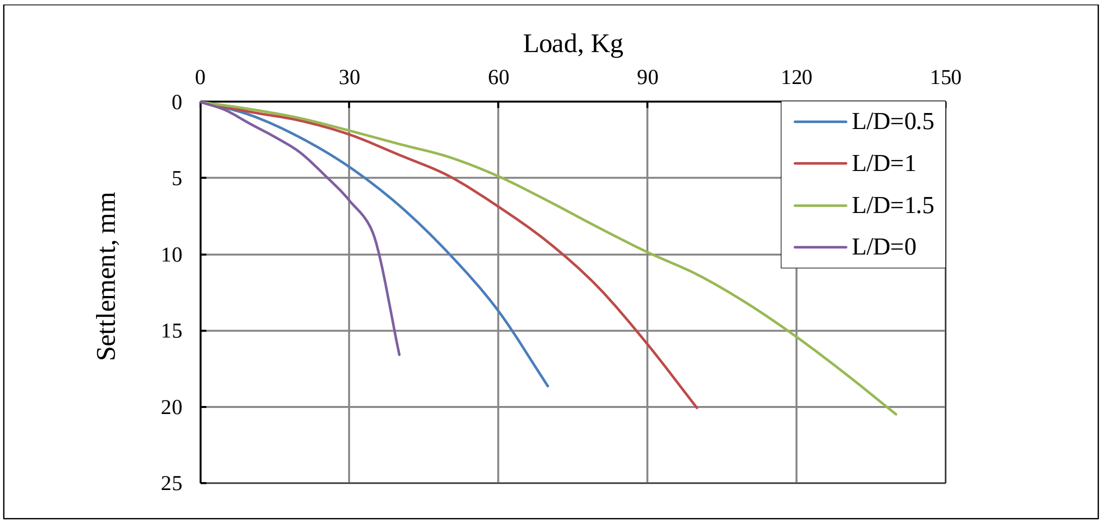

Figure 6. Load vs. foundation settlement relationship for foundation 90 mm in diameter at different skirt lengths

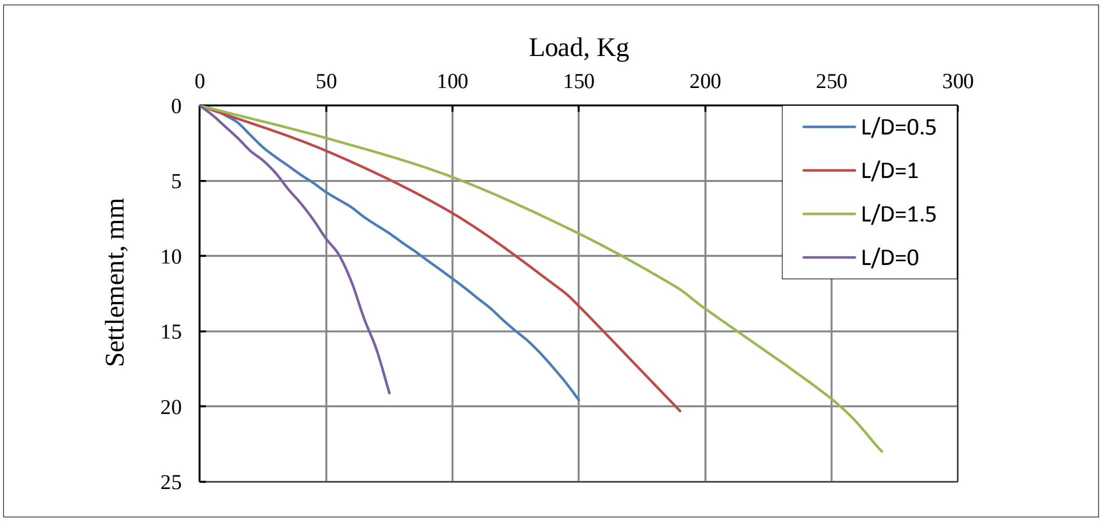

Figure 7. Load vs. foundation settlement relationship for foundation 120 mm in diameter at different skirt lengths

Figures 8, 9 and 10. illustrate the relationship between the load and settlement of foundations for foundation with closed end skirt.

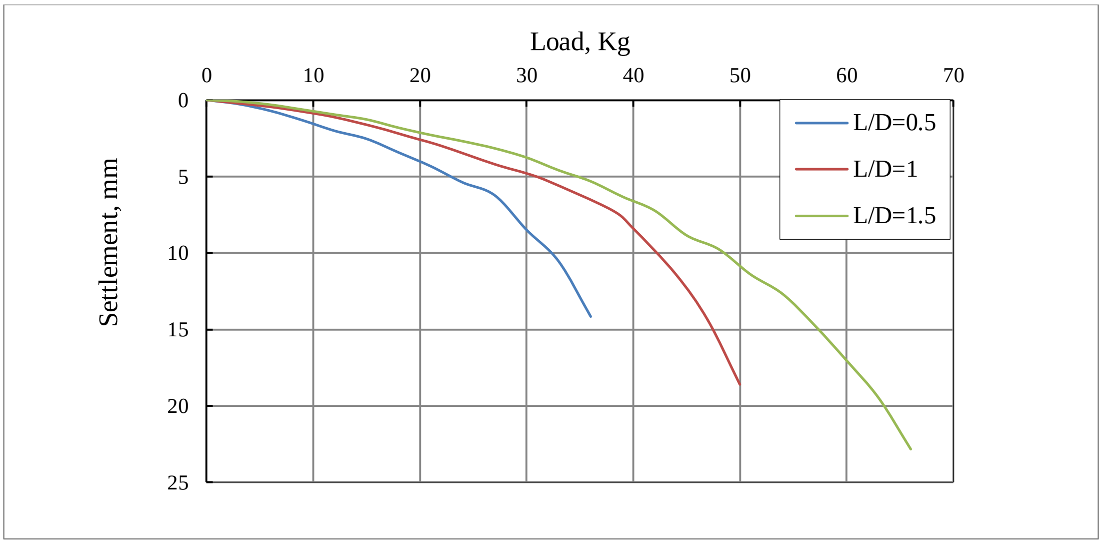

Figure 8. Load vs. foundation settlement relationship for foundation 60 mm in diameter at different skirt lengths

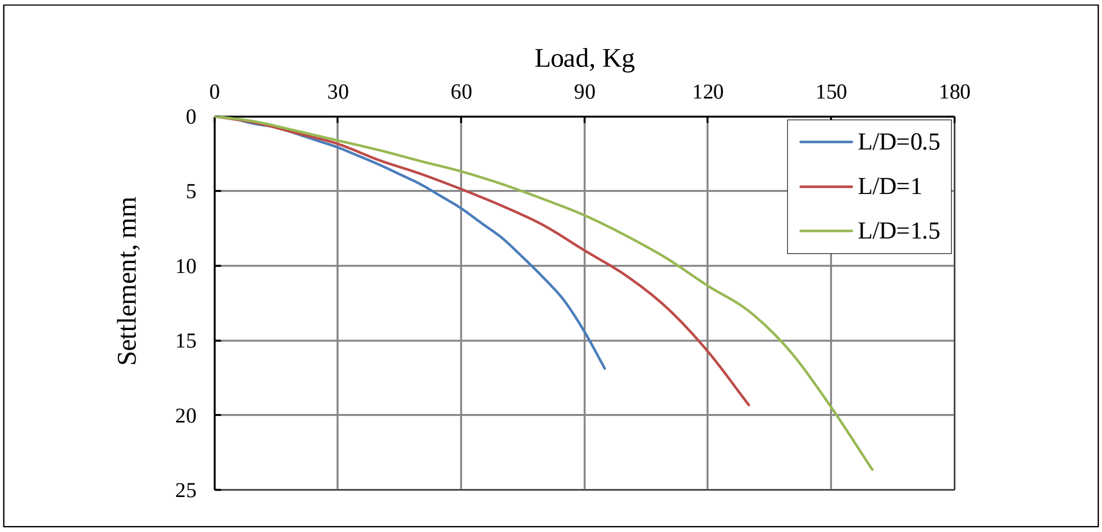

Figure 9. Load vs. foundation settlement relationship for foundation 90 mm in diameter at different skirt lengths

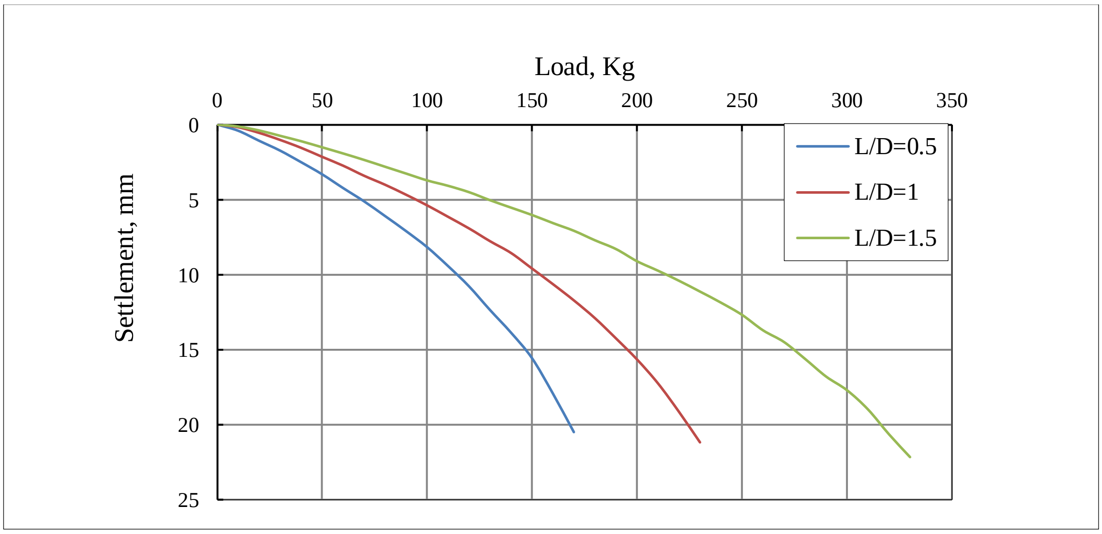

Figure 10. Load vs. foundation settlement relationship for foundation 120 mm in diameter at different skirt lengths

Each Figure is plotted for fixed foundation diameter and varied skirt lengths. It is clear that application of skirts improves the performance of foundations, enhance load carrying capacity of foundations and reduce foundations settlement. The magnitude of improvement increases with increasing skirt length as well as foundation size.

Comparing the curves of Figure 5, 6 and 7 at the ultimate settlement (the values that equal to 10% of foundation diameter), for different size of foundation 60, 90 and 120 mm, it can be seen that installation of skirt to the edge of foundations improve load carrying capacity from 17, 35 and 60 kg for foundation without skirt to 33, 84 and 188 kg for foundation with skirt having L/D ratio equal to 1.5, respectively. When comparing the curves of Figure 8, 9 and 10 at the ultimate settlement (the values that equal to 10% of foundation diameter), it show the same trend of behaviour for foundations with open end skirt. For different size of foundation 60, 90 and 120 mm, it can be seen that installation of skirt to the edge of foundations improve load carrying capacity from 17, 35 and 60 kg for foundation without skirt to 38, 107 and 241 kg for foundation with skirt having L/D ratio equal to 1.5, respectively.

Figures also revealed that for similar test conditions, foundations with skirt having closed end register higher failure loads compared to foundations with skirts having open end.

Table 2 shows percent increase in failure load for different L/D ratios of skirts as compared to L/D=0 for foundations with open end skirts.

Table 2. Percent increase in failure load for foundation with open end skirt

L/D ratio	% increase in failure load for different foundation diameter		
	60 mm	90 mm	120 mm`
0	-	-	-
0.5	29.4	34.3	71.7
1	82.4	97.1	135
1.5	100	140	213.3

Table 3 shows percent increase in failure load for different L/D ratios of skirts as compared to L/D=0 for foundation with closed end skirt.

Table3. Percent increase in failure load for foundation with closed end skirt

L/D ratio	% increase in failure load for different foundation diameter		
	60 mm	90 mm	120 mm`
0	-	-	-
0.5	52.9	108.6	113.3
1	100	157.1	186.7
1.5	123.5	205.7	301.7

For both skirt conditions, the increment in load carrying capacity is significant when the foundation size equal 120 mm and L/D ratio equal 1.5. In foundations with open end skirt, it was 213.3% while in foundation with closed end skirt, it was 301.7%.

For same skirt length and same foundation diameter, the percent increase in failure load of foundation with closed end skirt is more than that for foundation with open end skirt.

The enhancement in behaviour of shallow foundations with skirt can be explained as fallow: The installation of open end skirt confines the soil beneath the foundation and hence modifies the failure mode. The skirts resist the lateral movement of sand particles leading to a greater increase in load carrying capacity and considerable decrease in settlement. The confined soil behaves like a part of rigid foundation and transfer a major part of foundation load into a deeper zone. The deeper locations of the failure wedge increase the surface area of the skirt-model foundation.

In case of closed end skirt, when foundation with skirt and cap provided at its bottom, the depth of foundation increases and this will allow the depth of the failure surface to increase. The failure plane moves in the downward direction to the bottom edge of the skirt which leads to an increase in the area of the resisting soil around the skirt leading to increase in load carrying capacity because this combination (foundation and closed end skirts) starts to work as a one unit. This enhances load carrying capacity and improves the load-settlement behaviour of the foundation.

The ultimate load in case of closed end skirt is higher than ultimate load in case of open end skirt; this may be attributed to the increase in effective foundation depth and failure depth in case of closed end skirt is more than that in case of open end skirt.

4.2. Effect of Skirt Length

In order to evaluate the effect of the skirt length on foundation behaviour, loading tests were conducted on foundation with skirts. For each foundation diameter, skirts with three different lengths were used.

To understand the effect of changing the skirt length, the improvement in load carrying capacity is expressed using a non-dimensional parameter, called improvement ratio (IR). This parameter is defined as ratio of the failure load of skirted foundation to the failure load of normal foundation at a specified relative density of the sand bed. It should be noted that IR = 1 refers to the case of foundation without skirt (i.e. L/D =0).

The variation of IR is plotted against L/D ratios for various foundation diameters and shown in Figures 11 and 12.

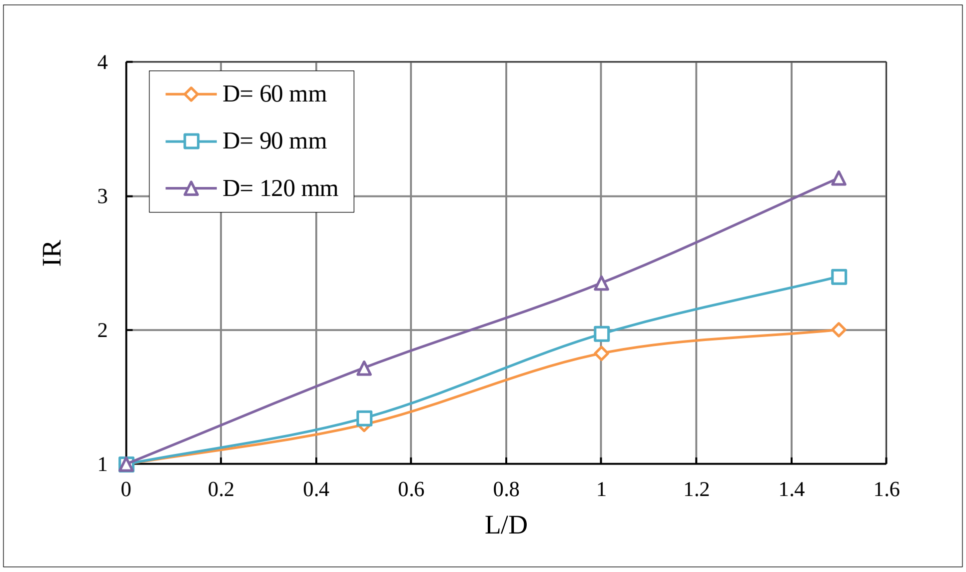

Figure 11. Variation of IR with L/D ratios for open end skirt at different foundation sizes

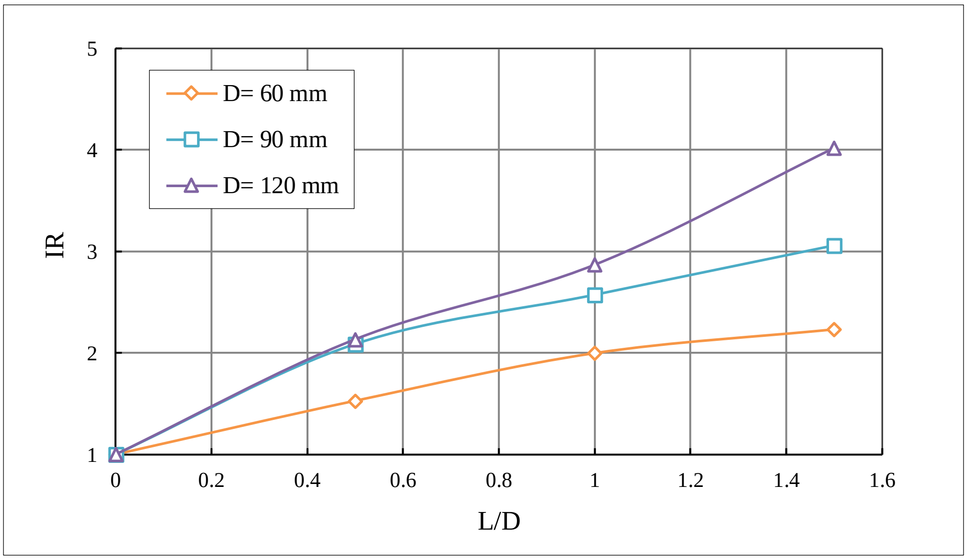

Figure 12. Variation of IR with L/D ratios for closed end skirt at different foundation sizes

It is noticed that, Increasing skirt length results in a greater improvement in improvement ratio both for foundation with open and closed end skirt. By means, as the length of skirt increases, the foundation is deeper seated and the foundation depth increases. As a result of that the IR increases and settlement decreases.

Figures above also show that the effect of increasing skirt length on the IR is observed to be most significant at L/D=1.5 for each foundations size, this mean if skirt length equals to 1.5 of foundation diameter (i.e. L/D=1.5) then the foundation performs better.

The rate of increase in improvement ratio with L/D ratio for foundation with open end skirt is not the same for foundations with closed end skirt for different foundation sizes, it is noticed that the cases where the skirt have closed end, result in an increase in IR when compared to the cases of open end skirt. It is clear that improvement in load carrying capacity is a function of skirt length and also depends where if the skirt has closed end or opened.

An enlargement in the surface area of skirt- foundation system is results due to the increase in skirt length; this transfers the foundation load to deeper depth leading to an increase in improvement ratio and decrease in settlement. Thus, higher ultimate loads can be obtained.

4.3 Effect of Foundation Size

To explore the effect of foundation size on the behaviour of skirted foundation, foundations of diameter 60, 90 and 120 mm were used for different skirt length.

Figure 13 and 14 illustrate the variation of IR with foundation size for various L/D ratios for open and closed end skirts.

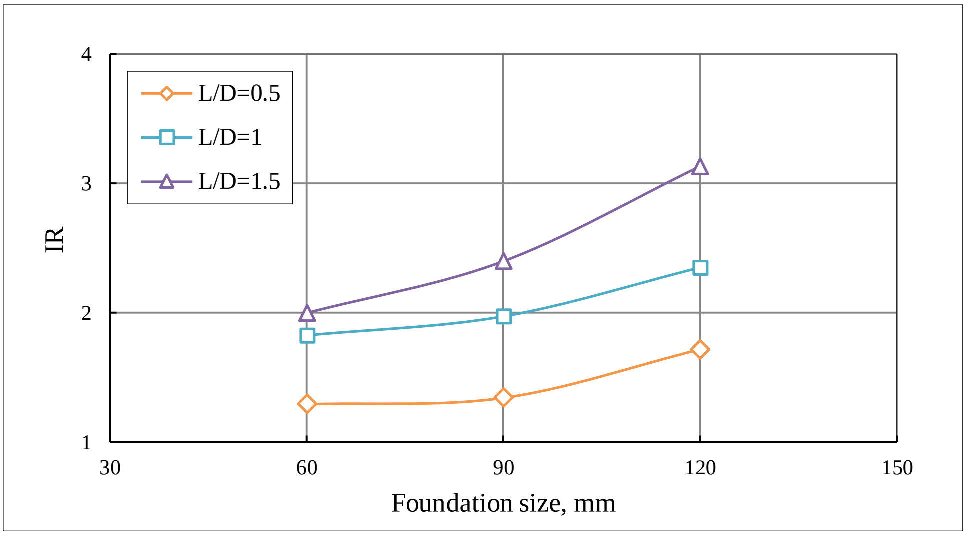

Figure 13. Variation of IR with foundation sizes for open end skirt at different skirt lengths

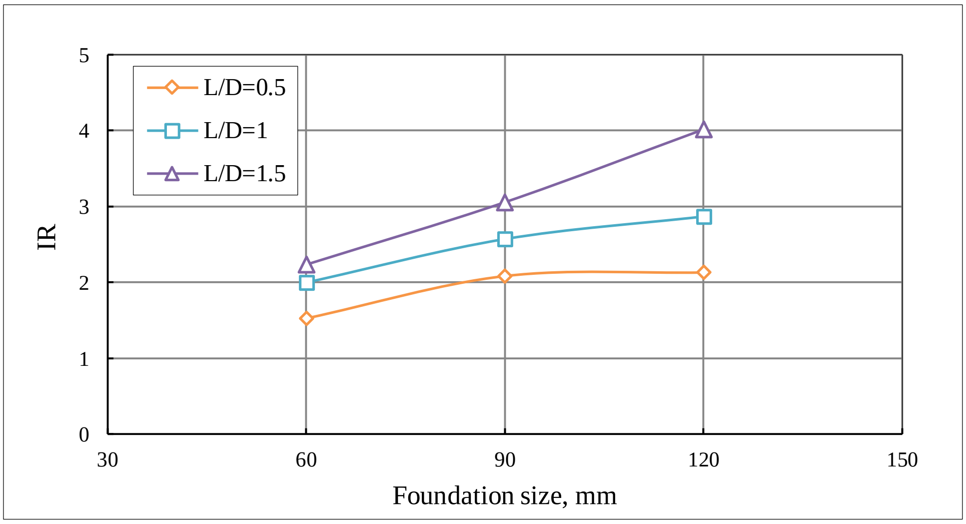

Figure 14. Variation of IR with foundation sizes for closed end skirt at different skirt lengths

It observed that, when the diameter of foundation increases the improvement ratio also increases. The IR for foundation of 60 mm diameter is less than that of 90 and 120 mm. Improvement ratio values for foundations with closed end skirt are higher compared to foundations with open end skirts at comparable conditions. For both skirt types, the highest improvement is found for foundation of 120 mm in diameter at all skirt lengths.

The increase in improvement ratio with the foundation diameter may be attributed to the increase in surface area at which the load is distributed on and increasing length of slip lines because the magnitude of bearing capacity is directly dependent on slip lines length (i.e. more lengthy slip lines results in greater bearing capacity), thus increasing slip lines length can be done by increasing the foundation diameter.

For all foundation sizes, the improvement ratio for skirt length equals to 0.5D and D is less than that of 1.5D. This trend proves the previous conclusion that as skirt length increases, the load carrying capacity increases. Figure 15 and 16 show the variation of failure load with respect to foundation size.

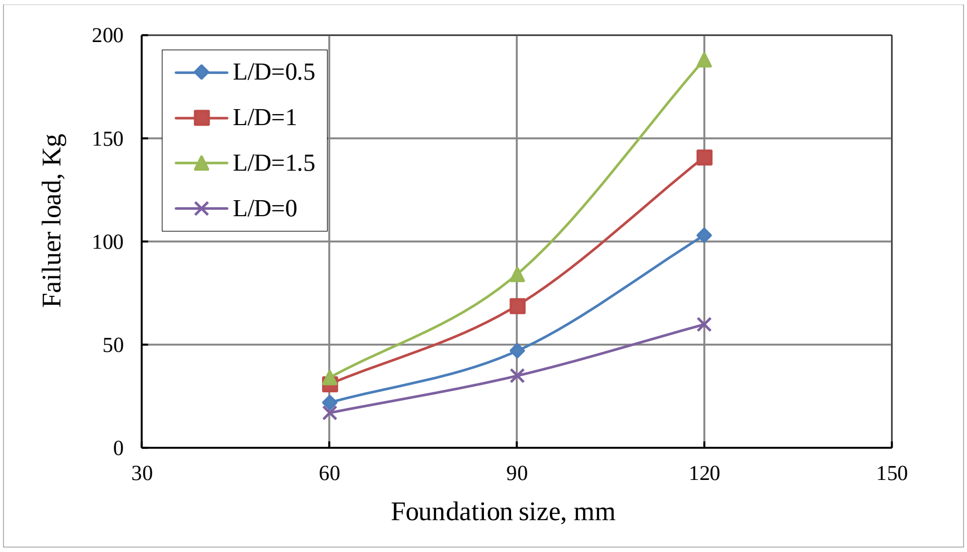

Figure 15. Failure load vs. foundation size for open end skirt at different skirt lengths

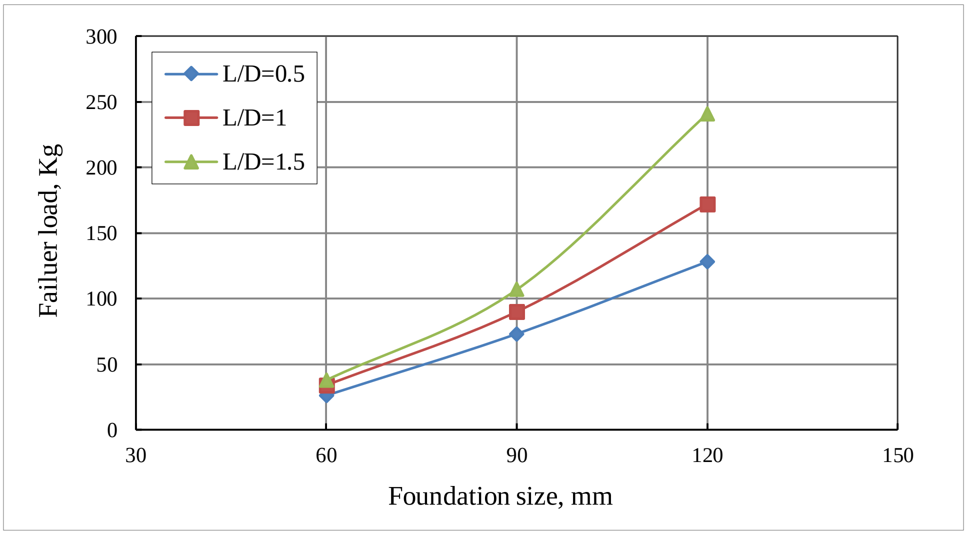

Figure 16. Failure load vs. foundation size for closed end skirt at different skirt lengths

From the graphs, the foundation diameter seems to have the same effect of skirt length on the failure load of sandy soil. It was found that as foundation size increases the failure load also increases for the same skirt length.

5. Conclusion

Based on the experimental investigation and test results of this study, following main conclusions are made:

- An inclusion of skirt attached to the edge of conventional shallow foundations supported on medium dense sand affects and modifies the foundation performance effectively by increasing its load carrying capacity and reducing settlement with different percentages.
- Using skirt can be considered as a method of improvement the load carrying capacity of foundations resting on sand. The effectiveness of this method depends on several parameters. These parameters involve the foundation size, skirt length, skirt condition (closed or open end skirts) and the interaction of skirt with the failure plane.
- The existence of skirt mitigates the vertical settlement. Skirted foundation can be used with structures that are sensitive to settlement to achieve the same allowable bearing capacity at much lower settlement.
- Increasing skirt length results in increasing load carrying capacity for the same foundation diameter. The maximum improvement is found to be at skirt length equals to one and half the foundation diameter (L/D=1.5) for all foundation sizes. This applies to cases either with open end skirt or closed end skirt.
- For same skirt length and condition, the load carrying capacity is observed to increase with increase the

foundation size. The optimum load carrying capacity reaches when the foundation size equals to 120 mm.

- The results showed that in case of open end skirt exhibited load carrying capacity lesser then in case of closed end at similar test conditions. The foundation with closed end skirt requires lower lengths and brings additional improvement to the foundations response.

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