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Numerical Analysis of Skirted Foundation on Sand for Load-Displacement Behaviour

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Abstract. A skirted foundation is a new solution that has been developed to improve the shallow foundation's bearing capacity and settlement. A skirt foundation comprises plates or skirts that wrap one or more sides of the soil mass beneath the footing to keep the loaded soil contained. Confinement works with the overlain foundation to practically transfer the superstructure load to the ground at the skirt tip, resulting in increased bearing capacity and reduced structure settlement. The current research adopted numerical analysis to examine the axially loaded shallow foundation resting on sand with and without a skirt. The behaviour of a skirted foundation has been studied in terms of skirt depth, vertical and inclined skirts, variations in skirt inclination, and one-sided, both-sided skirts. The effects of foundation size on bearing capacity and settlement of skirted foundations are also investigated. The findings show that when the skirt depth increases, the bearing capacity increases and settlement reduces. Further, it is found that the inclined skirt is quite promising as compared to the vertical skirt for inclination up to 12 degrees away from the foundation (positive skirt). However, the inclination of the skirt toward the foundation (negative skirt) has an adverse effect on the bearing capacity and settlement.

Keywords: Cohesionless soil. Skirt foundation, Settlement, Bearing capacity.

1 INTRODUCTION

Skirted foundations are shallow foundations in which the footing is upheld through vertical plates or skirts. It's one of the more innovative ways to improve the performance of shallow foundations by adding a skirt. The soil around the foundation performs a crucial role in the behaviour of the foundation. The skirted foundation is a foundation type where a vertical or slanted fence encompasses one or more borders of the soil below the footing. The skirts provide a walled-in area where the soil is monitored and filled in as a unit to transfer superstructure load to the soil at the skirt tip, resulting in an increase in bearing limit and a decrease in building settlement. Geotechnical experts are looking for an alternative technique to increase the bearing limit and reduce foundation settlement. While many methodologies of soil adjustment are highly recognised, they can be expensive and are restriction for site conditions. Some circumstances where it is challenging to apply those methods to existing platforms (Naik et al., 2015). For those cases, a skirt foundation might be an effective solution for increasing the bearing limit and reducing foundation settlement. Footing laid on the ground having skirt walls at the boundaries to restrict the soil below it. This detention of soil additionally controls the tilt and accordingly expands the bearing limit of the foundation. In this way, a substitute methodology is expected to enhance the bearing limit of the footing by utilizing a structural skirt fixed at the boundary. This improvement method does not require soil excavation and is not limited by the presence of a high water table. The vertical and horizontal load capacity of footing is improved by confinement and restricted to sliding. Subsequently, it could transform into a substitute approach for enhancing the bearing capacity of footing. This numerical analysis has been done to sort out the approach to know the foundation's performance with two sides, vertical and inclined skirt.

Skirted foundations can be a low-cost option for structures built on granular soils with high water tables, such as those found in many waterfront and nearby shore developments. Despite this, research into the performance of skirted shallow foundations resting on soils and carrying vertical loads is quite limited. This study aims to determine the impacts of lateral sand confinement by comparing the performance of skirted foundations to those of surface foundations. As a result, bearing capacity and settlement extents were used to illustrate such consequences. This should assist in forecasting how skirted foundations will behave under structural loading.

This work aims to innovate a strategy to increase the bearing limit and diminish the settlement of the foundation laying on the soil by skirt establishment.

2 Literature Review

Bell (1991) makes sense that shallow seaward establishments gain their strength by having the establishment situated on the seabed. They can be idealised as huge round establishments exposed to vertical, horizontal and transient loads. Bransby and Randolph (1998) demonstrated that soil footing geometry and strength profiles affect longitudinal and vertical limits using finite element and plastic analysis. Yun and Bransby (2003) compared the load-displacement reaction from centrifuge test data to the finite element result of a circular skirt footing with varying roughness and skirt profundity up to five times the diameter of the base. It was discovered that compared to a typical foundation, a skirted foundation increases the horizontal burden limit by roughly 3-4 times. Alaghbari and Mohamedzein (2004) organised several foundation model experiments to investigate the factors that influence skirted foundation behaviour. Elements incorporate foundation friction, skirt profundity, skirt lateral roughness, skirt solidness, and soil compaction. Because of these boundaries, they propose a condition for skirted nails. Alaghbari (2007) led a progression of tests on the circular establishment with and without skirt structure in an enormous tank to concentrate on the settlement of round establishment in the sand. These trial results show that primary layers diminish subfloor settlement as a function of applied pressure and skirt profundity and change in foundation settlement behaviour. Bransby and Yunand (2007) used analytical and experimental methods to demonstrate the vertical bearing limit of skirted foundations on typically consolidated undrained soils. They show that the boundary of the skirted foundation in the influence of vertical load normally conveys as though it were a strong groundwork with an embedment profundity equivalent to the depth of the skirt. Kudsk et al. (2008) used ordinary and mathematical finite element soil association to show the world's largest jack-up, skirted footing, and changing stresses on stratified soil. An envelope for offshore foundations with similar soil characteristics was provided based on the results. Yun and Bransby (2009) demonstrated how deformity of the soil between the external skirts could result in an essentially lower bearing limit of the establishment than a comparable inserted strong groundwork. The particular geometry of the establishment should be considered during the design. Wakil (2010) conducted 12 burden tests on small-sized rounded baseboards subjected to horizontal loads. From lab testing, the skirts were viewed as ready to change the failure method of the shallow pins from sliding to a turning system. Skirts appended to the foundation of the nail essentially expanded the transverse capacity of the shallow nail. Eid (2013) used a small-scale physical model to conduct experiments. The bearing limit and settling of the foundation were evaluated with footing size, sand shear strength, and skirt depth. The findings reveal that the wall footing has a similar load-bearing limit and settling to, but is not identical to, a pile foundation of equal width and profundity. Randolph and Gourvenec (2012) used finite element analyses to test the rounded skirt establishment and time-subordinate response to uniaxial vertical stresses. The findings show that the consolidation reaction is influenced by the roughness of the skirt-soil contact and the embedment ratio. The results of Pusadkar and Bhatkar (2013) reveal that using a skirt surface for the foundation significantly impacts working on the bearing limit. This improvement increases as the skirt depth increase with varied raft sizes. Mana et al. (2012) discussed the failure mechanism of skirted foundations subjected to uplift and compression loadings.

3 Methodology

Although several well-known and well-developed soil stabilisation methods may be prohibitively expensive and constrained by site factors. In some circumstances, applying them to existing foundations can be difficult. This method of enhancing bearing capacity requires no soil excavation and is not restricted by a high groundwater table. The numerical analysis is used to investigate the load-carrying carrying capacity of foundations with different skirt ratios. The vertical skirts are supposed to increase foundation capacity by trapping soil beneath the raft and between the skirts and transferring applied weight to the ground at the skirt points (Hu et al., 1999). The shear failure of the soil beneath the shallow footings is the leading cause of failure. Such failures can be avoided by enclosing the earth beneath the footing in some form of enclosure. Skirts with foundations operate as a soil plug to transfer super-structural weight to the earth and form an enclosure where the soil is tightly confined. In this analysis, two parameters were evaluated. The bearing capacity for a constant settlement comes first, followed by the settlement for a constant bearing pressure. The performance of the skirted raft footing is investigated using Mohr-Coulomb models for various skirt depths and footing sizes. The bearing capacities of foundations are determined through numerical analysis of skirted foundations utilising numerous skirts in this work.

4 Numerical Analysis

A comprehensive 2D finite-element analysis is used to study the effects of skirts on the behaviour of axially strained surface foundations resting on the sand. Steel sheets with a thickness of 50 mm were used to simulate the skirts in the analysis. This thickness was chosen to match the rigidity (moment of inertia) of commercially available steel sheet-pile sections used for foundation skirting. Fifteen-node planar strain elements are adopted to represent sand, footing, and skirts. To lessen the boundary effect, the distance between the finite-element mesh boundary and the foundation edges was set to 15B (where B is the width of the footing). Footing and skirts are made of linear elastic fabrics. Sand behaviour is represented using the Mohr-Coulomb model. The stress-settlement linkages have no evident break-point or peak. As a result, the ultimate bearing capacity was determined in this numerical study as the stress corresponding to a settlement. The numerical research revealed considerable differences in the foundation types' behaviour when comparing the stress-settlement correlations. These adjustments were mirrored in the overall displacement diagrams generated from the numerical investigation by applying the same applied stress to the surface and skirting foundations. The saturated unit weight taken for soil is 20 $kN/m^{3,}$ While for Y_{unsat} is 17 kN/m^3. While the value of cohesion is zero, the friction angle has the value of 35^0 for the analysis. Using comprehensive finite-element analysis, the impacts of skirts on the behaviour of a uniformly loaded surface foundation on the sand are explored. The geometry of the finite element soil model employed in this study is 15BX20B, with B= 10 unit to 20 unit raft sizes and Ds (skirt depth) of 0.5B, 1B, 1.5B, 2B, 2.5B, and 3B skirt depths. The soil employed for the analysis was essentially sandy cohesionless soil. Fifteen-node triangular elements are used to depict the behaviour of sand in the Mohr-Coulomb model. The skirts and the footing were both considered linear elastic materials.

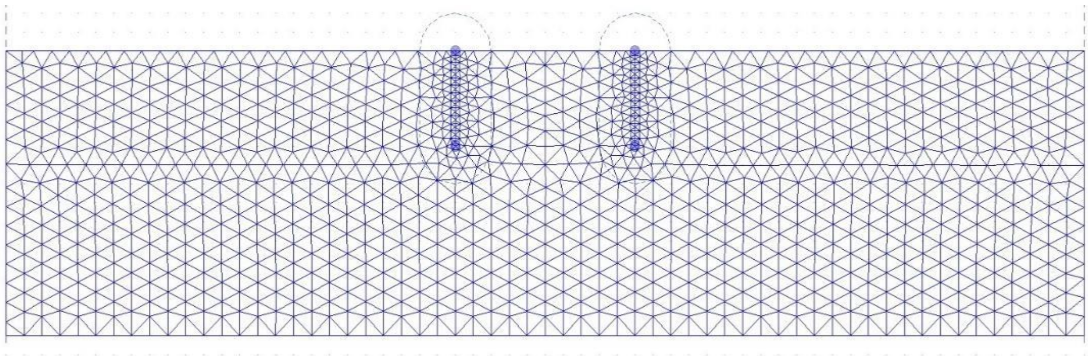


Fig. 1. A generated mesh of the model.

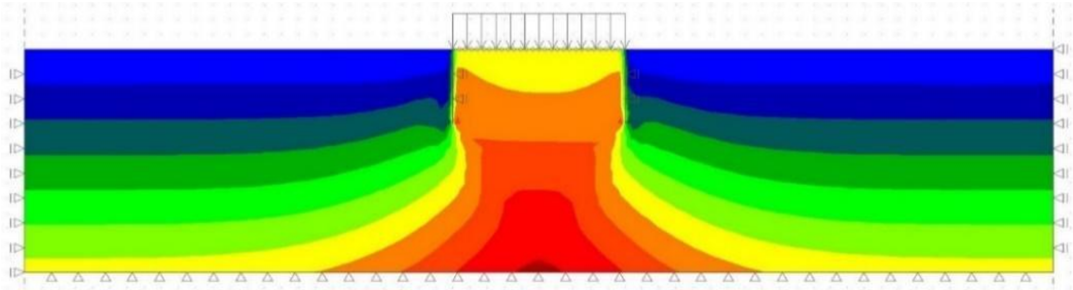


Fig. 2. Represents the variation of stress across the skirted footing.

The total stress variation as the load for specific settlement to the structure is shown in figure 2 above. The figure shows the variation in stress near the provided skirt. It shows the variation of stress across the boundary and along the depth. The change in settlement and load-carrying capacity can be seen in the above image. The variation for skirt ratio from 0 to 3 is utilised to build the model in the same manner for all the models, and the value of the respective settlement is noted down. The variation in settlement with various skirt ratios and the corresponding differential change is noticed. The results are analysed, and the discussion is processed based on the change that is seen for different skirt ratios and varied skirt orientations.

5 Results and Discussions

The foundations of 10-unit, 15-unit & 20-unit widths with different skirt depths for the vertical skirt are analysed. This study generated six numerical models by altering the skirt's depth below the ground while keeping the foundation width constant. The skirt ratio is adjusted in 0.5 increments from zero to three. As the depth of the skirt increases, there is a change in settling and bearing capacity.

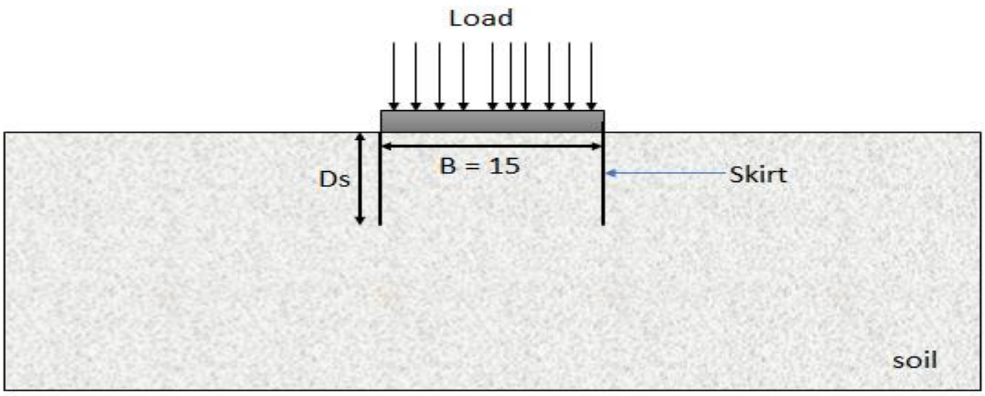


Fig. 3. Geometry model of foundation with vertical skirt having the foundation of 15 m width

Table 1 shows how the length of the skirt beneath the soil affects the settlement of a foundation with a skirt. The breadth of the foundation is kept constant, while the depth of the skirt varies. Models (a) to (g) depict seven different foundation models with skirts. Based on the findings, the footing accomplishes less settlement by increasing the length of the skirt in comparison to the unskirted surface foundation. By keeping the foundation width constant and adjusting the length of the skirt that has been given around the foundation edges in a vertical direction, it has been observed that by increasing the length of the skirt, a lower value of the settlement is achieved compared to a surface foundation. As the skirt ratio varies from

0.5 to 3 at 0.5 intervals, a percentage improvement in bearing capacity of roughly 12 to 50% is noticed compared to the surface foundation. The load-carrying capacity of a foundation with a skirt varies as the length of the skirt beneath the soil increases, as shown in Table 2. Only the depth of the skirt varies, while the foundation width remains fixed. Models (a) through (g) denote seven different foundation models with a skirt. It is observed that the surface foundation's bearing capacity increases with the skirt's length. The bar chart in figure 4 below depicts the percentage improvement in foundation-bearing capacity due to the addition of the skirt. By gradually increasing the skirt ratio, it is seen that there is a significant improvement in bearing capacity. In this analysis, the variation for different permissible settlements is also observed, which results in a near-identical percentage difference in foundation carrying capacity. By increasing the skirt ratio from 0 to 3, the bearing capacity is increased by 50%. It means that when the length of the skirt increases, the bearing capacity also enhances. The number of times bearing capacity increased over the unskirted surface foundation (bearing capacity ratio) was calculated using the preceding graph plotted between Qsk/Qsu Vs skirt ratio. It is discovered that the bearing capacity is improved by approximately 1.5 times. When a similar analysis is performed for B= 10 unit, 15 unit and 20 unit, it is observed that keeping the skirt away from the centre results in a drop in bearing capacity. As a result, when the value of B is low, that is, low footing width, the value of bearing capacity improves significantly more than in other cases. The graph in figure 6 illustrates this by showing the variety in percentage increases in bearing capacity for B equal to 10, 15, and 20.

Table 1. Settlement of foundation of 15 unit width with different skirt depth for the vertical skirt.

Model	Ds/B	Settlement for 25 kN/m^2 (mm)	Settlement for 50 kN/m^2 (mm)	Settlement for 100 kN/m^2 (mm)	Settlement for 150 kN/m^2 (mm)	Settlement for 200 kN/m^2 (mm)	Settlement for 250 kN/m^2 (mm)
Model a	0	20.2	40.5	81.1	122.2	163.1	204.4
Model b	0.5	20.2	40.4	81.0	122.0	163.0	204.0
Model c	1	19.8	39.6	79.4	120.3	160.3	200.9
Model d	1.5	19.1	38.2	76.8	116.3	155.3	195.2
Model e	2	18.4	36.8	74.1	112.5	150.2	189.4
Model f	2.5	17.8	35.6	71.7	107.9	146.4	183.0
Model g	3	17.3	34.6	69.7	105.1	142.0	178.1

Table 2. Bearing capacity of foundation for 15 m width (B=15m) with different skirt depths for different allowable settlement

Model	Ds/B	Bearing capacity for 25mm settlement (kN/m^2)	Bearing capacity for 40mm settlement (kN/m^2)	Bearing capacity for 50mm settlement (kN/m^2)	Bearing capacity for 75mm settlement (kN/m^2)	Bearing capacity for 100mm settlement (kN/m^2)
Model a	0	33.10	52.79	65.84	98.27	130.47
Model b	0.5	36.88	58.81	73.4	109.53	145.47
Model c	1	40.09	63.99	79.87	119.4	158.87
Model d	1.5	42.75	68.27	85.27	127.53	169.73
Model e	2	45.11	72.07	89.93	134.60	179.2
Model f	2.5	47.23	75.47	94.20	141.00	187.67
Model g	3	49.14	78.53	98.00	146.73	195.33

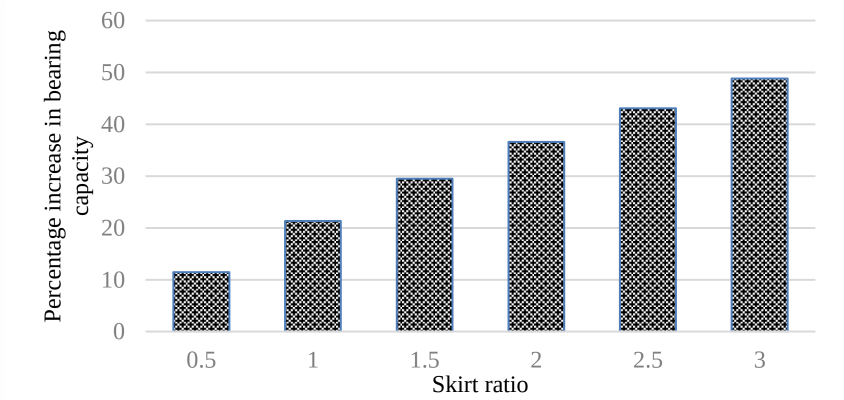


Fig. 4. Percentage increase in bearing capacity for B=15.

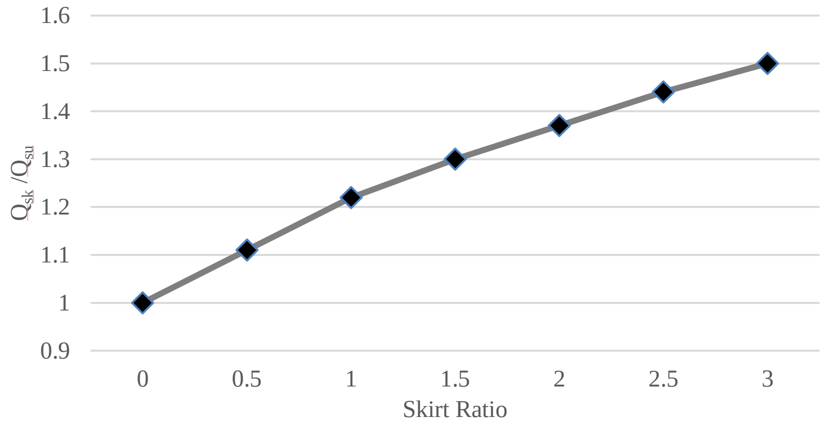


Fig. 5. Variation of bearing capacity ratio with the skirt ratio.

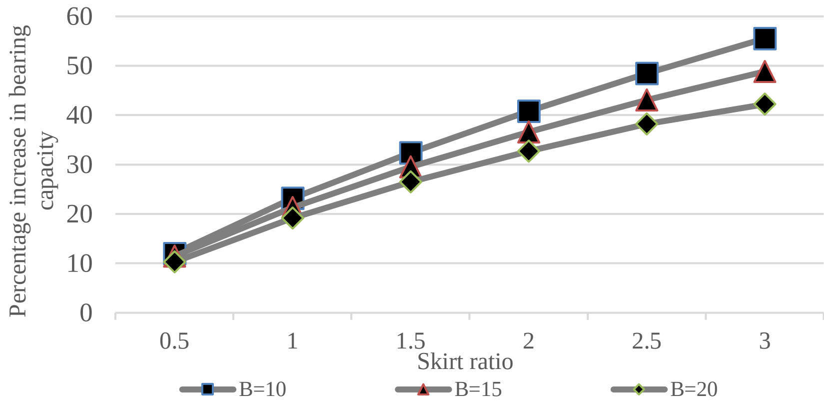


Fig. 6. Percentage increase in bearing capacity for B equals 10, 15, and 20 units.

When comparing the bearing capacity and settlement for one-side and two-side skirts of 15-unit width, it is clear that two-sided skirts are always preferable to one-sided skirts. The bar chart (figure 7) shows that varying the skirt ratio from 0.5 to 3 increases the bearing capacity for two-sided skirts over one-sided skirts. For similar conditions, the percentage decrease in settlement for two-sided skirts over one-way skirts is around 1.5 times. Six numerical models are generated by altering the depth of the skirt below the ground while keeping the foundation's width constant. In this study, the inclined skirt is modelled at a 5-

degree to 30-degree angle from vertical. The skirt ratio is adjustable in 0.5 increments from zero to three. With increasing skirt depth, there is a change in settlement and bearing capacity.

Table 3. Comparison of one-side and two side vertical skirts.

Ds/B	Settlement for 100 kN/m^2 (mm) for one side vertical Skirt	Settlement for 100 kN/m^2 (mm) for two-side vertical Skirt
0	81.0	81.0
0.5	81.1	81.0
1	80.3	79.4
1.5	79.2	76.8
2	77.8	74.1
2.5	76.5	71.7
3	75.3	69.7

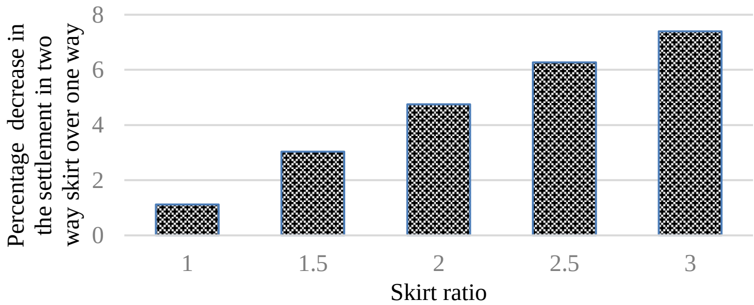
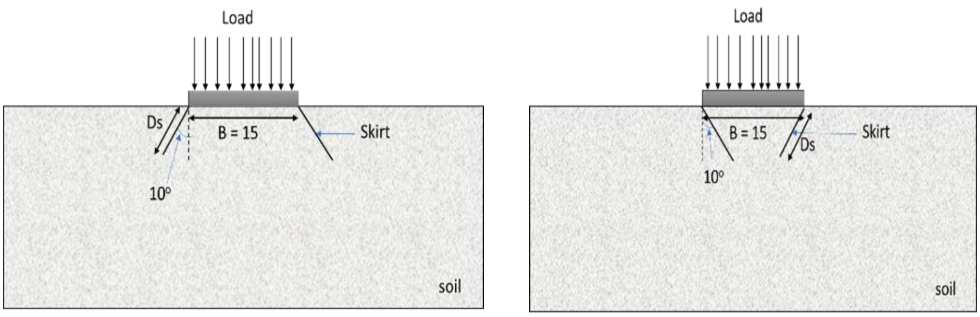


Fig. 7. Percentage decrease in the settlement in two-side skirts over one-side skirts.



. **Fig. 8.** Geometry model of foundation with two-sided (a) 10° positive and (b) 10° negative skirt.

Table 4 shows how the length of the skirt beneath the soil affects the settlement of a foundation with a skirt. The breadth of the foundation is kept constant, while the depth of the skirt varies. Models (Ia) to (Ig) represent seven different foundation models with skirts. Based on the findings, one can accomplish less settlement by increasing the length of the skirt in comparison to that of the surface foundation. Table 5 shows how the bearing capacity of a foundation with a skirt varies as the length of the skirt beneath the soil increases. The breadth of the foundation is kept constant, while the depth of the skirt varies. Models (Ia) to (Ig) represent seven different foundation models with skirts. According to the analysis, increasing the length of the skirt can result in a higher bearing capacity than what we currently have for the surface foundation. According to the investigation, this inclined skirt has a bearing capacity enhancement of roughly 50%.

Table 4. Settlement of foundation of 15 m width (B=15m) with different skirt depth for 10 degrees inclined skirt.

Model	Ds/B	Setlement for 25 kN/m^2 (mm)	Setlement for 50 kN/m^2 (mm)	Setlement for 100 kN/m^2 (mm)	Settlement for 150 kN/m^2 (mm)	Settlement for 200 kN/m^2 (mm)	Settlement for 250 kN/m^2 (mm)
Model Ia	0	20.2	40.5	81.1	121.9	162.7	203.6
Model Ib	0.5	20.0	40.0	80.3	120.7	161.3	202.0
Model Ic	1	19.7	39.4	79.2	119.3	159.8	200.5
Model Id	1.5	18.9	38.1	76.7	115.9	155.5	195.6
Model Ie	2	18.3	36.8	74.3	112.3	150.9	190.0
Model If	2.5	17.8	35.7	72.0	108.9	146.5	184.8
Model Ig	3	17.3	34.7	70.0	106.1	142.8	180.2

Table 5. Bearing capacity of foundation for 15 m width (B=15m) with different skirt depths for various allowable settlements for 10 degrees inclined skirt.

Model	Ds/B	Bearing capacity for 25mm settlement (kN/m^2)	Bearing capacity for 40mm settlement (kN/m^2)	Bearing capacity for 50mm settlement (kN/m^2)	Bearing capacity for 75mm settlement (kN/m^2)	Bearing capacity for 100mm settlement (kN/m^2)
Model Ia	0	33.1	52.79	65.84	98.27	130.47
Model Ib	0.5	38.18	61.06	76.27	114.27	151.47
Model Ic	1	41.10	65.63	81.93	122.67	163.33
Model Id	1.5	44.09	70.4	87.93	131.73	175.4
Model Ie	2	46.67	74.53	93.13	139.47	185.73
Model If	2.5	48.97	78.27	97.73	146.4	195
Model Ig	3	51.03	81.53	101.87	152.6	203.27

Table 6. Comparison of settlement for 10 degrees positive and negative skirt.

Ds/B	Settlement for 25 kN/m^2 (mm) When B=15 for the vertical skirt	Settlement for 25 kN/m^2 (mm) for 10 negative skirt	Settlement for 25 kN/m^2 (mm) for 10 degrees positive skirt
0	20.2	20.2	20.2
0.5	20.1	20.0	19.9
1	19.8	19.8	19.7
1.5	19.1	19.2	18.9
2	18.4	18.5	18.3
2.5	17.8	18.0	17.8
3	17.3	17.6	17.3

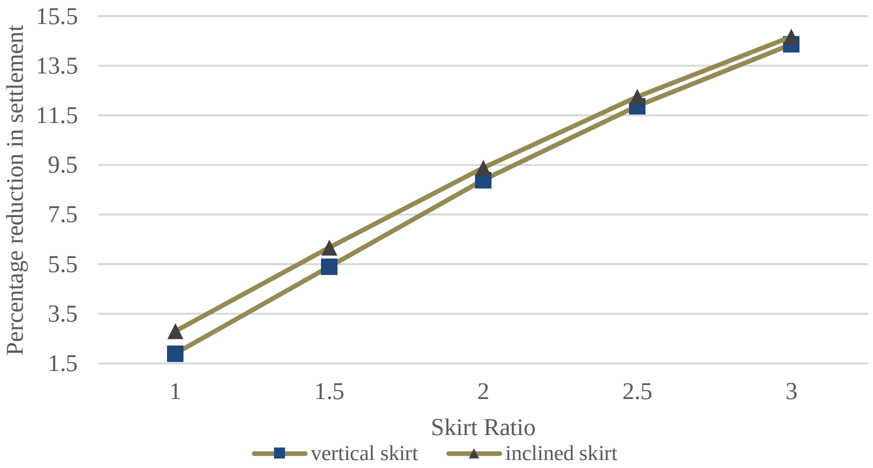


Fig. 9. Percentage reduction in settlement for the vertical and inclined skirt

When a similar analysis is performed for two-sided 10^0 interior (negative)Inclined Skirt and compared with vertical and 10^0 positive inclined skirts, while examining the graph shown in figure 9, it is observed that the fluctuation of the percentage decrease in settling for inclined skirts against vertical skirts, from the analysis it is found that the inclined skirt with a 10-degree inclination outperforms the vertical skirt with the same attribute. A 10-degree inclined skirt away from the foundation and a 10-degree negative inclined skirt are also checked. The 10-degree negative inclined skirt has a lesser bearing capacity improvement than the 10 degrees positive inclined skirt, according to the findings of this experiment. Comparing vertical and inclined skirts for various authorised settlements, inclined skirts perform better than vertical skirts. Further investigation reveals that, up to a point, an inclined skirt outperforms a vertical skirt in terms of increasing load-carrying capability. It means that while comparing the inclined skirt for different angles, it is discovered that as the inclination increases beyond a certain point i.e. 12 degrees in our analysis, the load-carrying capacity decreases and the settlement increases because it is unable to bind soil between the footing's edges.

Table 7. Comparison of bearing capacity for 10 degrees positive and negative skirt.

Ds/B	Bearing capacity for 25mm settlement (kN/m^2) for a 10-degree interior inclined skirt	Bearing capacity for 25mm settlement (kN/m^2) for a 10-degree exterior inclined skirt
0	33.1	33.1
0.5	34.28	38.18
1	38.78	41.10
1.5	41.01	44.09
2	42.93	46.67
2.5	44.58	48.97
3	46.25	51.03

6 Conclusions

Some of the significant conclusions that can be drawn from the analysis are as follows:

- It is inferred from the analysis that a reduction in settlement of about 15 percent is observed on the installation of the skirt.
- One side skirt's functioning capacity is also much lower than that of both side skirts.

- Based on the findings, it is deduced that varying the inclination of the skirt initially yields a favourable result, i.e., the settlement decreases. There is a decline in bearing capacity after the inclination exceeds 12 degrees.
- A variation in the width of 10 to 20 units at a 5-unit interval reveals that extending the skirt beyond the centre causes an increase in settlement and a reduction in bearing capacity owing to independent action.
- When comparing the results obtained from the vertical and inclined skirts for inclination up to 12 degrees, it is observed that the result obtained from the inclined skirt is quite promising.
- The investigation also revealed that a skirt angled toward the foundation (negative skirt) has a detrimental effect, but a skirt angled away from the foundation (positive skirt) results in higher bearing capacity.

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