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Effect of Partial Saturation on Ultimate Bearing Capacity of Skirted Foundations

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HIGHLIGHTS

- The soil load carrying capacity in the case of unsaturated soil is the highest.
- A structural skirt increases the bearing capacity, reduces the settlement, and modifies the load settlement behavior of the footing.
- A significant decrease in the load-carrying capacity was observed as the soil below the base of the foundation gets fully saturated.

ARTICLE INFO

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ABSTRACT

Skirted foundations are one of the solutions proposed to increase the bearing capacity of the soil. They assist in increasing the load and depth of failure in weak ground or soils with low shear resistance and reducing the foundation settlement if a soil improvement method cannot be applied or the cost of implementing deep foundations increases. This study examined and investigated the extent of soil bearing of skirted foundations on sandy soils and studied the effect of soil saturation cases and three cases of water content reduction to measure the matric suction value of unsaturated soil. A physical model was created to simulate the strip foundation and compare these cases (dry-fully saturated-partially saturated). It was found that the soil load carrying capacity in the case of unsaturated soil is the highest, where matric suction is at a depth of 450 mm, followed by the dry case and then the saturated case as it represents the weakest state of the soil.

1. Introduction

One of the improvement methods used to increase the bearing capacity of shallow foundations provides skirts that fulfill the bearing capacity requirement and provide additional horizontal strength. The skirt transfers the load into the deeper, usually stronger soil, mobilizing higher carrying capacity than a surface foundation. Researchers have attempted to estimate the capacity of skirts and their criteria. Numerical analysis, theoretical formulation, model tests, and prototype field tests were used to estimate the capacity for support of the surrounding footings and their influencing parameters. Byrne et al. [1] presented the results of a laboratory study with a special focus on the loads relevant to the wind turbine problem on rocky, low-sand foundations under monotonic loading. The study consists of several lengths of skirts relative to the diameter of the base, mineralogy, and sand density. The results of vertical bearing capacity tests and simple theoretical expressions based on the standard bearing capacity formula have been presented. Yun and Bransby [2] studied the problem by conducting centrifuge model tests on skirted foundations on drained, loose sand subjected to mixed loads (horizontal, vertical, and moment loading). The tests revealed that the horizontal bearing capacity of the foundation with the skirt was enhanced to approximately 3-4 times compare to that of the raft footing. Their findings also revealed that the failure mode had shifted from sliding to rotating. El Sawwaf and Nazer [3] used laboratory model studies to investigate the ultimate bearing capacity of a circular foundation seated on restricted sand. The influence of cell diameter, foundation embedded depth, cell height, and cell depth to the top was investigated. They found that sand confinement enhances bearing load capacity**.** Villalobos [4] studied scale skirted foundations in loose and dense sand subjected to monotonic vertical loading. The analysis took different skirt lengths, mineralogy, and sand density into account. In the failure analysis, the bearing capacity formulation was used. El Wakil [5] studied the effect of skirts on the bearing capacity of shallow footings by performing laboratory tests on circular steel footings of various diameters. The effect of sand density and skirt length on the ultimate load achieved was examined. The skirt increased the ultimate load of shallow footings by up to 6.25 times for the research parameters and variables, demonstrating that it improved the sustainability of shallow foundations to the applied load. The performance of skirted footing is also

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dependent on the relative density of sand and the ratio of skirt length to footing diameter. Treaty [6] proposed an experimental investigation to estimate the effectiveness of a circular foundation with and without a skirt and evaluate its capacities as horizontal and vertical load carriers with various sand-resting relative densities and varying ratios of skirt length to diameter. Model foundations with diameters of 40 mm, 60 mm, and 100 mm were employed with sand relative densities of 90%, 75%, 60%, 45%, and 30%, respectively. Only 60 mm diameter foundations were used in the horizontal loading experiments, with the same relative densities and skirt ratios. Both rough and smooth skirt foundations were used in the tests. It was concluded that the skirts increase load-carrying capacity in the range of 11.2% to 30%, reduce the foundation settlement, and adjust stress-strain behavior**.** Eid and Hisham [7] proposed a comprehensive numerical analysis that was used to study the behavior of axially loaded skirted shallow foundations resting on the sand. The investigation included surface, pier, and skirted square foundations with various shear strength qualities lying on the sand. This research indicated that skirted foundations have bearing capacity and settlement values that are similar to, but not identical to, pier foundations of the same width and depth. With rising skirt depth and decreasing relative density of sand, the bearing capacity of a shallow foundation improves. Settlement reduction may exceed 70% in the case of having skirt-depth/foundation-width of 2.0. Krishna et al. [8] pre-tested the carrying capacity of the sponsored square foundation on sandy soil. The sand was laterally delimited by hollow steel-plate boxes. The effect of altering confinement depth, foundation embedment depth ratio, and sand relative density was investigated. The results showed that load carrying capacity improves with confinement depth, peaking at (D/B=2), and it also increases with embedment depth, peaking at (De/D=0.5) for all sand relative densities. Momeni et al. [9] conducted an experimental and numerical analysis to predict the bearing capacity of a novel precast thin-walled spread foundation known as the Industrialized Building System (IBS foundation) in loose and dense sands. When a thin-walled foundation was employed instead of a simple foundation, the bearing capacity increased by practically a factor of two. Thakare and Shukla [10] offered information on the performance of rectangular skirted foundations, and lateral loading tests were conducted. The effect of embedment depth of skirt to foundation width (D/B) ratio on the ultimate horizontal loads achieved by the foundation was explored by adjusting the D/B ratio to 0.5, 1, 1.5, and 2, the number of skirts attached to the foundation, and varied load inclinations. The number of skirts and the D/B ratio were found to greatly boost foundations' ultimate lateral load-carrying capacity. Khatri et al. [11] used laboratory experiments to study the pressure-settlement behavior and bearing capacity of square and rectangular skirting foundations resting on sand and exposed to a vertical load. They employed a 50 mm and 60 mm wide base with a length/width ratio of 1 and 2. Sand with varying relative densities was used (Dr= 30%, 50%, 70%, and 87%). The skirt depth ranged from 0.25 B to 1.0 B. The findings indicate that using a structural skirt greatly improves the foundation's carrying capacity. The increase in bearing capacity was roughly linearly related to the depth of the skirt. Mahmood [12] tested plain strain models on sand beds with various particle size distributions prepared in a loose condition (Dr. 30 percent). At varying D/B width ratios at the skirt depths of (0.5, 1.0, 1.5, 2, and 3), a strip footing model with a skirt has been assembled and loaded upright until it fails. According to test data, the improvement ratio increased straight up to D/B 1.5 and subsequently declined**.** Sajjad, and Masoud [13] examined physical modeling to evaluate the performance of skirted shallow foundations lying on a sand bed. To investigate the behavior of circular and skirted foundations subjected to vertical loads, laboratory tests were conducted on small-scale foundation models. The effects of foundation diameter, the relative density of sand, skirt depth, and roughness of the model surface on skirted foundations' bearing capacity and settlement were studied. The model tests have shown that using skirts improves the bearing capacity and settlement values of skirted foundations compared with shallow foundations without the skirt. The improvement in bearing capacity and a reduction in settlement of shallow foundations increase with increasing the skirt depth, roughness of skirt sides, and decreasing the relative density of sand. Arekal et al. [14] investigated the effect of vertical inserts or skirts on the bearing capacity of shells and bucket basements in c-soils. The load settlement curve revealed that increasing the thickness and depth of vertical insertions increases bearing capacity by up to eight times. The carrying capacity of c-φ soil is also affected by the design of the footing. Square skirted legs have a higher carrying capacity than those circular and rectangular footings with vertical insertions. Alzabeebee [15] studied the efficiency of using these skirts to reduce settlement produced by machine vibration. However, machines are very sensitive to settlement, and the foundations of these machines should be designed properly to ensure that the settlement produced due to machine vibration is very small. The analyses showed that the use of skirts reduces the settlement produced due to machine vibration. However, the percentage decrease of the settlement is remarkably influenced by the density of the soil and the frequency of vibration. It rises as the frequency of vibration increases and declines as the soil density rises. Al-Aghbari and .Mohamedzein [16] conducted a series of tests on model footings in a large tank, and the footings were instrumented to measure normal stresses and settlement. The test results indicate that the skirts increase the bearing capacity and reduce the footing settlement. The improvement in the bearing capacity is up to about 470% for a surface footing with a skirt of a depth of 1.25B. The skirts also reduced the settlement of the footings to 17% of the original settlement of a surface footing without skirts. A modified bearing equation was proposed for circular footings with skirts. Most previous studies on the subject did not consider the effect of saturation conditions on improving the amount of soil bearing capacity with skirt foundations. Therefore, this study considers the soil improvement for skirted foundations in dry, fully saturated, and partially saturated soils and compares them with different length-to-width ratios.

2. Research Methodology and Experimental Program Materials

2.1 The Properties of the Soil

The soil used in the research was provided by the Abu Nawaz area. It was analyzed at the construction laboratory of the Sarah Technical Institute to identify its properties and conduct the sieve analysis, where it was classified with the symbol SP (poorly graded sand) by USCS according to ASTM D422-00 [17], as shown in Figure 1. The physical properties of the soil with the relevant specification used in the testing are summarized in Table (1).

Table 1: The physical properties of sand

Index property	Value	Specification
D10 (mm)	0.16	-
D30 (mm)	0.21	-
D60 (mm)	0.29	-
Cu and Cc	1.71 and 0.89	-
Specific gravity, Gs	2.65	ASTM D854-00 [18]
Maximum dry unit weight (kN/m^3)	17	ASTM D4253-00 [19]
Minimum dry unit weight (kN/m^3)	14.6	ASTM D4254-00 [20]

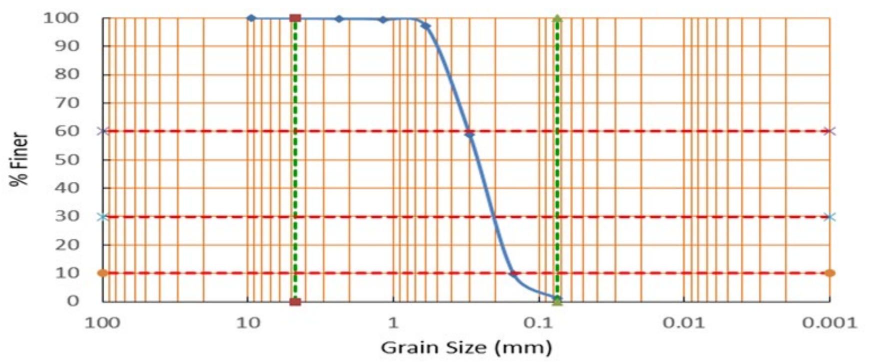


Figure 1: The soil's grain size distribution

2.2 Models for Skirted Foundation

As indicated in Figure 2, the skirt foundation model was created. It consists of a steel strip footing and steel plates on all sides. The strip footing model has a width of 5 cm, a length of 25 cm, and a thickness of 1 cm. It is connected to the skirt plate through threaded holes, evenly spaced on the skirt plate to achieve variable D/B ratios by rotating the screw bolt placements.

Figure 2: Model of skirted foundation

2.3 Test Methodology

Figure (3) shows a setup for the testing model, which consists of all the apparatus used, a soil box with inner dimensions of (600 mm x 600 mm x 700 mm) and the height was developed by Mohamed and Vanapalli (2006) to facilitate the process of soil saturation and desaturation. A steel frame, a load cell, and a load indication make up the device (saturation, drainage). A (1 ton) load cell is used to evaluate the compression stress of the skirted base model. The suitable vertical load in compression is operated by a strain control screw jack attached to an AC-controlled engine at various speeds. The loading rate is 0.5 mm per second, and the compression settlement is calculated using an optical dial gauge.

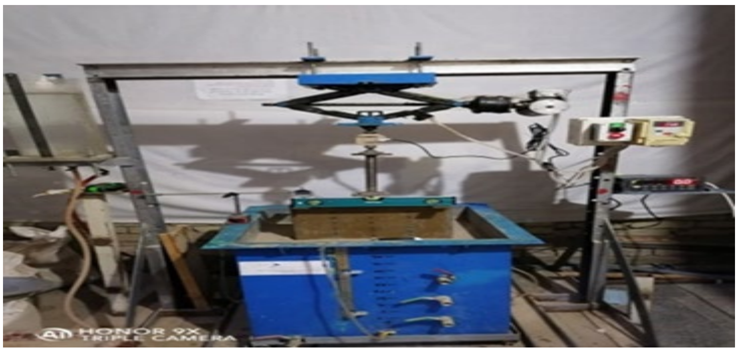


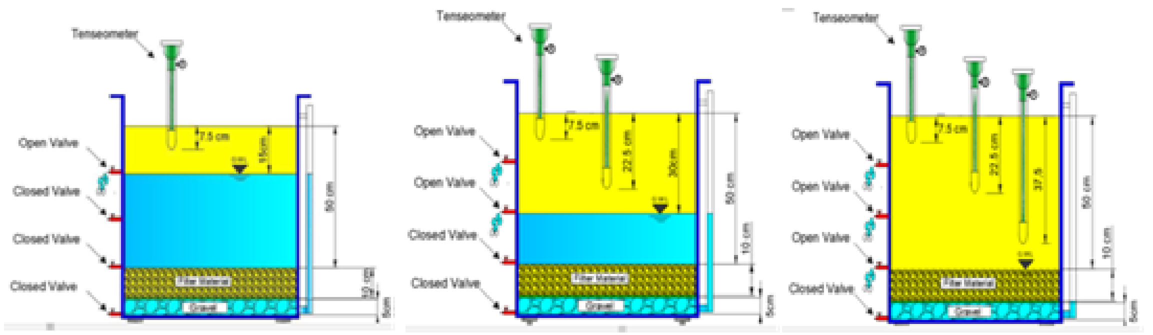
Figure 3: Setup of the testing model

2.4 Installation Procedures Model With a Skirted Foundation

The skirt was pushed into the soil until the footing within the skirt was placed on the soil surface after the last layer of the bed floor and filter layer were completed. The magnetic holder was attached to the container's sides, and dial gauges with a precision of (0.01 mm) were installed on the footing edges.

2.5 Suction Profile Setup for a Partially Saturated Soil Model

After a full saturation of the soil model, drawn water level variations cause changes in the suction profile. By decreasing the water level beneath the soil surface to various depths (150, 300, and 450 mm), suction was measured at the center between the soil surface and water level. The procedure was repeated for each lowering, where matric suction was measured after 24 hours. Finally, direct measurement of suction by the Tonometer apparatus was carried out, and the matric suction increased as the water table value decreased. Figure 4 shows the Densitometer and its accessories and the profile suction test for the 3 phases.



Profile suction test (150mm) profile suction test (300mm) profile suction test (450mm)

Figure 4: Densitometers and the profile suction tests

3. Results and Discussion

To determine the effect of the saturation actions of the foundation, loading experiments were carried out with skirts on the foundation. Skirts of 5 different lengths were used for each foundation width and three saturation conditions (dry, fully saturated, and partially saturated in three lowering water table cases). After drawing the relationships between the settlement of foundations with stresses' loaded for all cases, overlap relationships were drawn between three states of saturation for each density to compare soil capacity and different ratios of footing length to widths of (0, 0.5, 1, 1.5, 2, and 3).

3.1 Average Matric Suction

Tables (2, 3, and 4) show the average matric suction for loose, medium, and dense sand, respectively, obtained by the Densitometer instrument in this study.

Table 2: The average matric suction for loose sand results (D.r = 30%)

Soil saturation case	Lowering of the water table from the top of the soil (mm)	The average matric suction (kPa)	Average grav. water content (%)
Fully saturated	0.0	0.0	--
Partially Saturation	150	6.5	16.4
	300	7.3	14.3
	450	9.5	12.8

Table 3: The average matric suction results for medium sand. (D.r = 50%)

Soil saturation case	Lowering of the water table from the top of the soil (mm)	The average matric suction (kPa)	Average grav. water content (%)
Fully saturated	0.0	0.0	--
Partially Saturation	150	7.6	18.0
	300	8.4	16.2
	450	11.4	14

Table 4: Average matric suction results for dense sand. (D.r = 70%)

Soil saturation case	Lowering of the water table from the top of the soil (mm)	The average matric suction (kPa)	Average grav. Water content (%)
Fully saturated	0	0	--
Partially Saturation	150	4.4	11.0
	300	5.45	9.5
	450	7.62	6.9

3.2 Effect of Saturation Condition At Loose State Sand

Figures (5-10) show the stress settlement relationship of skirt footing resting on loose density sand with different D/B ratios of (0, 0.5, 1.0, 1.5, 2.0, and 3.0) under different saturation conditions (dry, fully saturation, and partially saturation of three different matric ratios). The figures show that the minimum bearing capacity at a full saturation condition and the maximum bearing capacity is not at dry soil but at partial matric suction of 9.5 kPa. This might be due to an increase in effective stresses with increasing the lowering of the water table, which increases the bond among particles and the attractive force formation among sand particles.

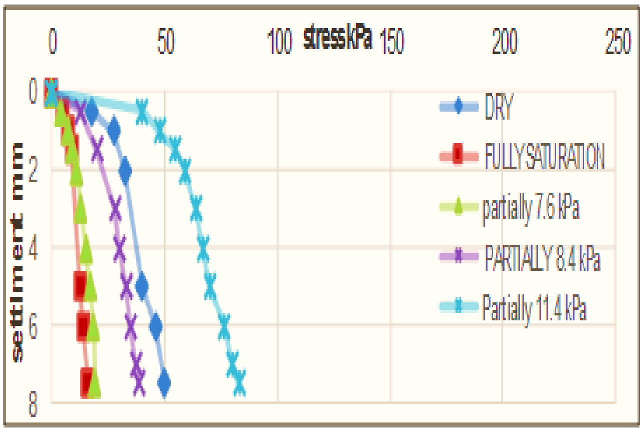


Figure 5: Applied stress vs. settlement relationship for the foundation of D/B=0 for loose sand with different saturation conditions

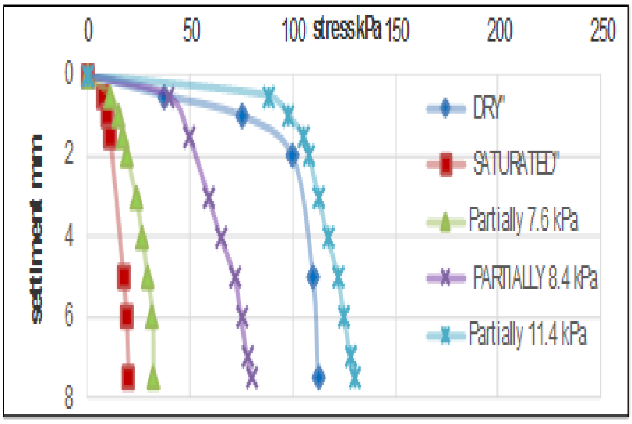


Figure 6: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=0.5 for loose sand with different saturation conditions

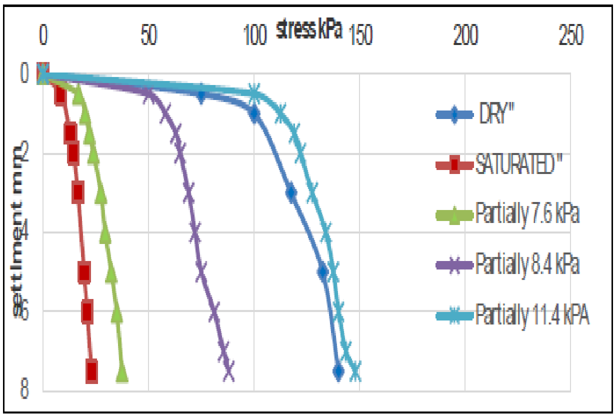


Figure 7: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=1 for loose sand with different saturation conditions

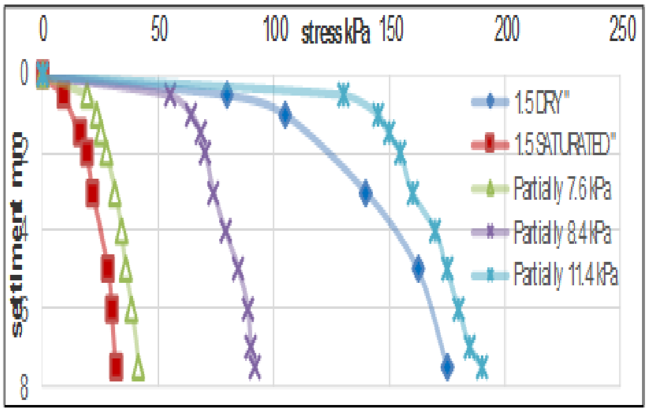


Figure 8: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=1.5 for loose sand with different saturation conditions

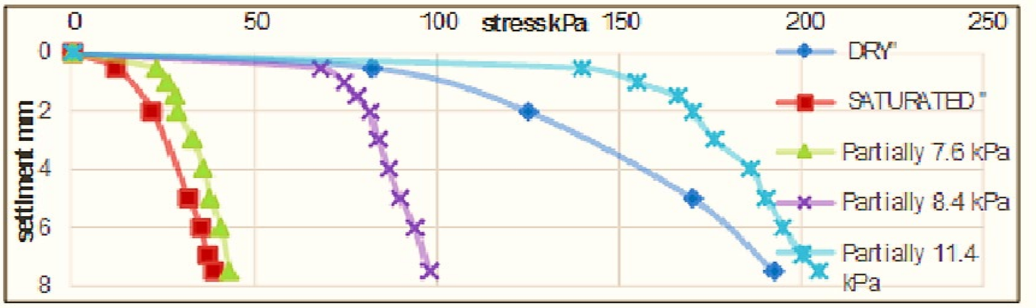


Figure 9: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=2 for looses And with different saturation conditions

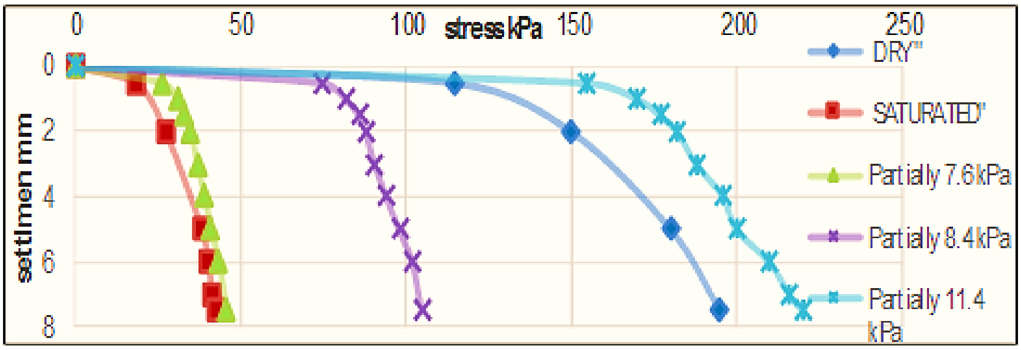


Figure 10: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=3 For loose sand with different saturation conditions

3.3 Effect of Saturation Condition at Medium State Sand

Figures (11-16) show the stress settlement relationship of skirt footing resting on medium density sand with different D/B ratios of (0, 0.5, 1.0, 1.5, 2.0, and 3.0) under different saturation conditions (dry, full saturation, and partial saturation of three different matric ratios). The figures show that the minimum bearing capacity is at a full saturation condition and the maximum bearing capacity is at a partial saturation condition of matric suction of 11.4kPa. This might also be attributed to an increase in effective stresses with increasing the lowering of the water table, which increases the bond among particles and increases the formation of the attractive forces among sand particles.

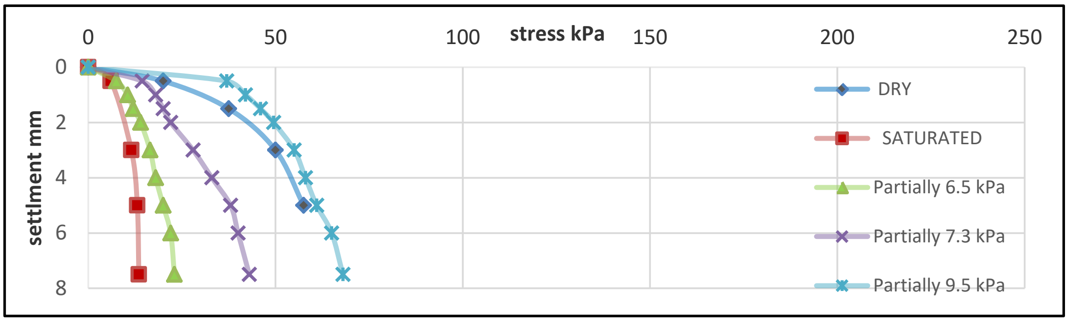


Figure 11: Applied stress vs. foundation settlement relationship for the foundation of D/B=0 for Medium sand with different saturation conditions

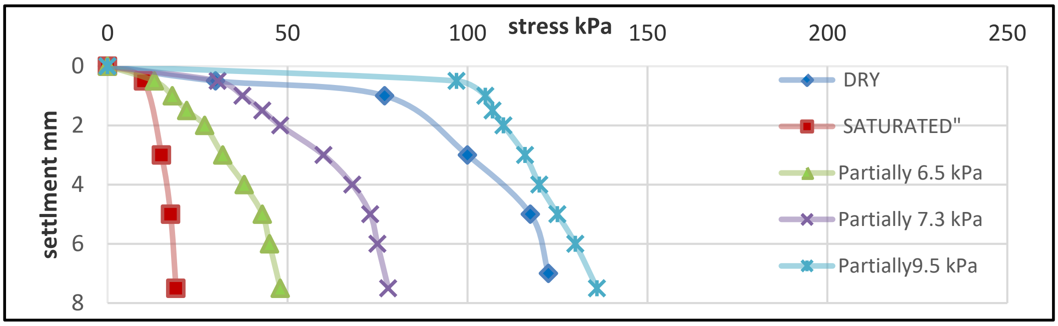


Figure 12: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=0.5 for medium sand with different saturation conditions

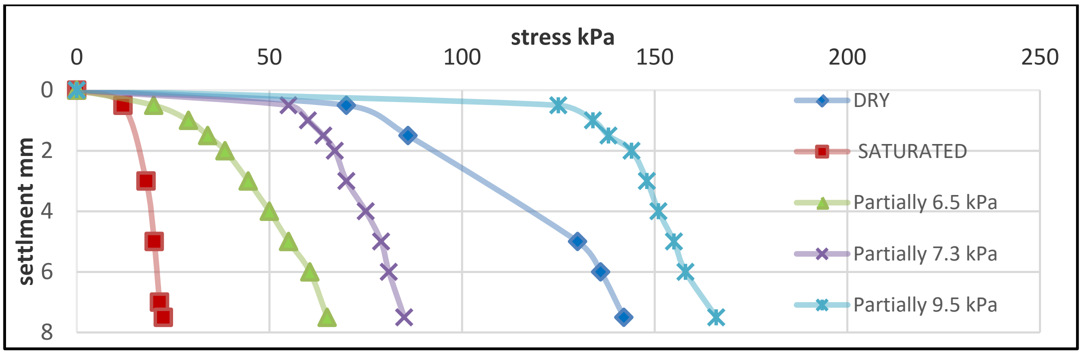


Figure 13: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=1 For medium sand with different saturation conditions

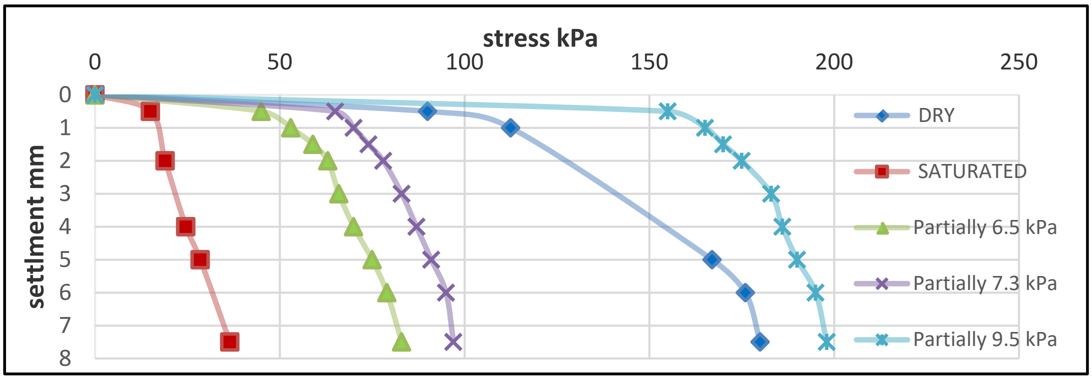


Figure 14: Applied stress vs. foundation settlement relationship for the skirted foundation of L/B=1.5 For medium sand with different saturation conditions

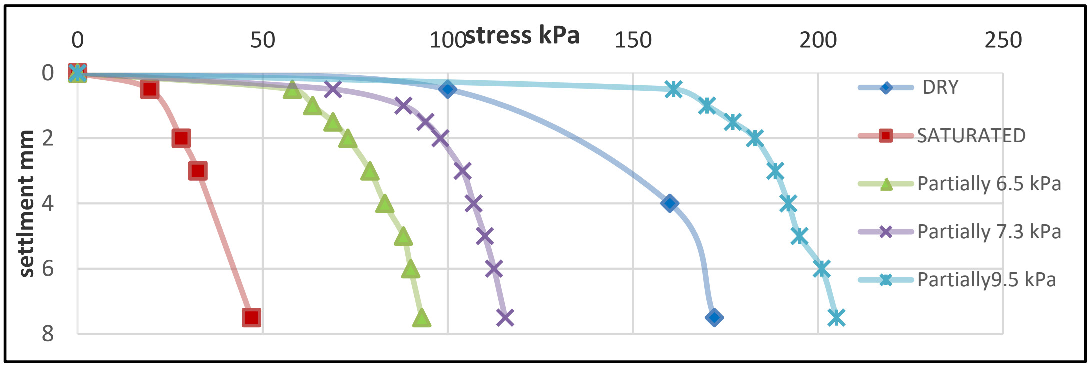


Figure 15: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=2 For medium sand with different saturation conditions

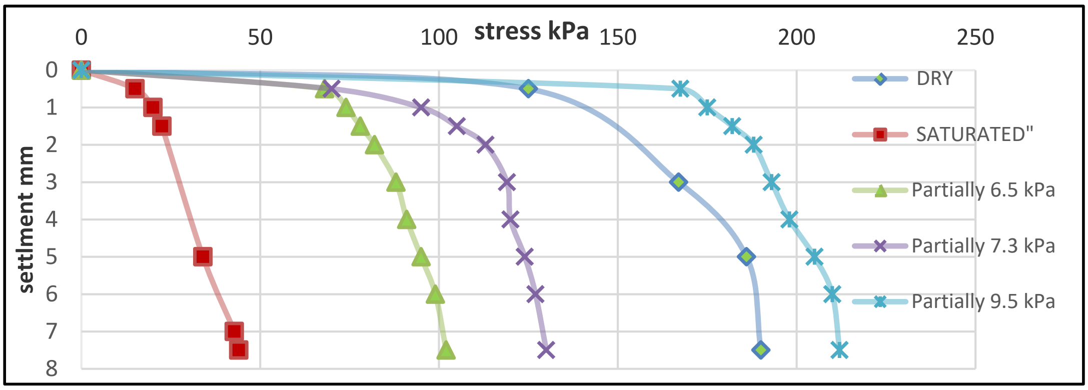


Figure 16: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=3 For medium sand with different saturation conditions

3.4 Effect of Saturation Condition on the Test Result of Dense State Sand

Figures (17-22) show the stress settlement relationship of skirt footing resting on dense sand with different D/B ratios of (0, 0.5, 1.0, 1.5, 2.0, and 3.0) under different saturation conditions (dry, full saturation, and partial saturation of three different matric ratios). The figures show the same behavior as the other densities. However, the minimum bearing capacity is also at a full saturation condition, and the maximum bearing capacity is at a partial saturation condition of matric suction of 7.62 kPa. This might also be attributed to an increase in effective stresses with increasing the lowering of the water table, which increases the bond among particles and increases the formation of the attractive forces among sand particles.

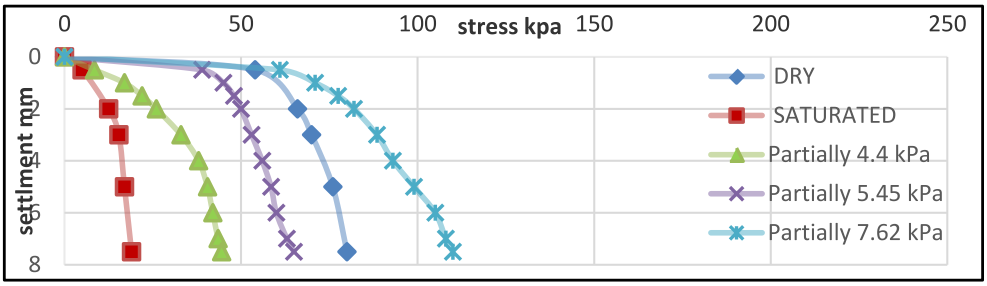


Figure 17: Applied stress vs. foundation settlement relationship for the foundation of D/B=0 for Dense sand with different saturation conditions

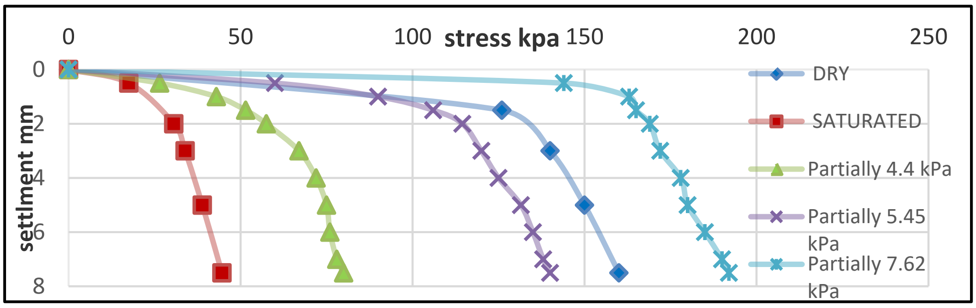


Figure 18: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=0.5 for dense sand with different saturation conditions

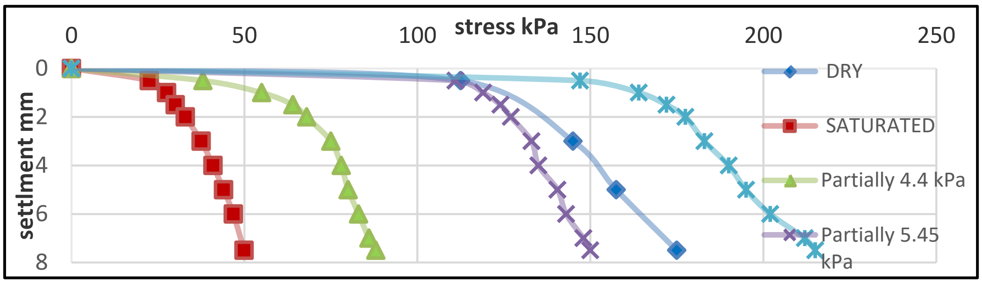


Figure 19: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=1 For dense sand with different saturation conditions

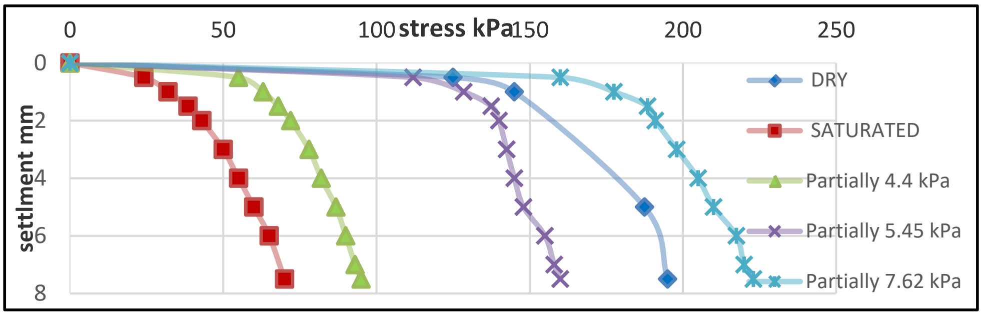


Figure 20: Applied stress vs. foundation settlement relationship for the skirted foundation of D/B=1.5 for dense sand with different saturation conditions

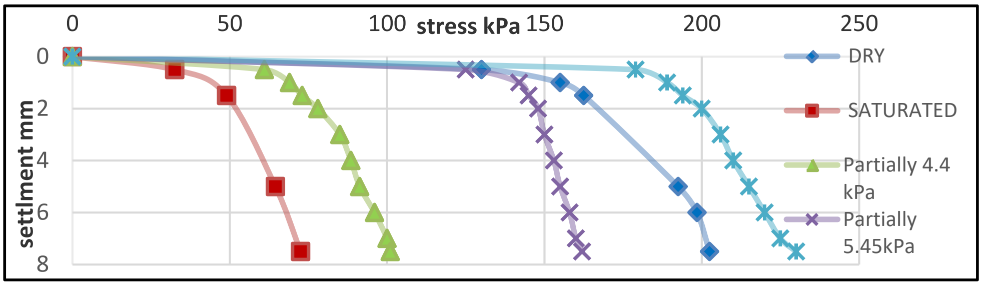


Figure 21: Applied stress vs. foundation settlement relationship for skirted foundation D/B=2 on Dense sand with different saturation conditions

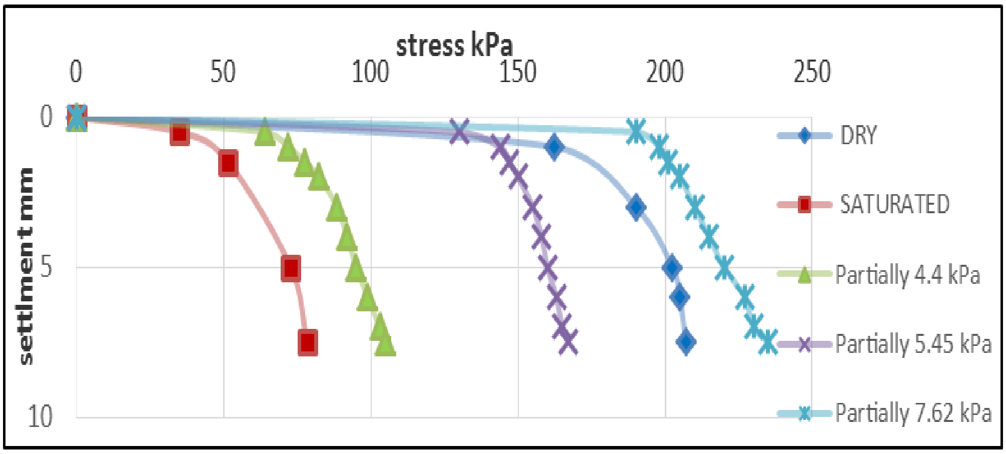


Figure 22: Applied stress vs. foundation settlement relationship for skirted foundation D/B=3 on Dense sand with different saturation conditions

3.5 Effect of Saturation Condition with Different Densities

The results of the ultimate bearing capacity are shown in Table (5). When comparing the saturation state with the dry state results for all the relative densities cases of (30%, 50%, and 70%), it is clear that due to maximum saturation, there is a significant decrease in the ultimate load-carrying capacity for all skirt footings with different D/B ratios and without skirts. Therefore, it is thought that the settlement of foundations with and without skirt increases dramatically as the soil gets saturated immediately below the foundation level; this can be due to various reasons: After saturation, the settlement of foundations results from the breakdown of the bonds among the soil particles, sand contains fine particles that establish a strong connection with coarse particles in dry conditions, and this bond disappears when the soil is saturated and may contribute to a significant settlement, and the soil also loses its stiffness when it saturates and settles more. Therefore, its capacity to accommodate the load that comes over its unit area is diminished. In addition, another cause of settlement can be explained in part by the process of water lubrication of the sand particles. These factors mainly result in a loss of soil strength, thereby reducing the carrying capacity of the load when the soil bed gets saturated.

In contrast, the results of the ultimate bearing capacity revealed that when the soil becomes partially saturated for different relative densities cases of (30%, 50%, and 70%). At matric suction of the 3rd lowering, the ultimate bearing capacity of soil increases due to an increase in the effective stress and the attraction forces introduced due to lowering the water table in cohesion less soils. But when the soil becomes partially saturated at matric suction of the 1st and the 2nd lowering for all relative densities, the ultimate bearing capacity has a lower value than the dry and highest value and the fully saturated sand. Figures (23-24-25) show the relationship between the ultimate load and D/B ratios for foundation resting on dry, fully saturated, and partially saturated cases at loose sand, medium dense, and dense sand for different matric suction values.

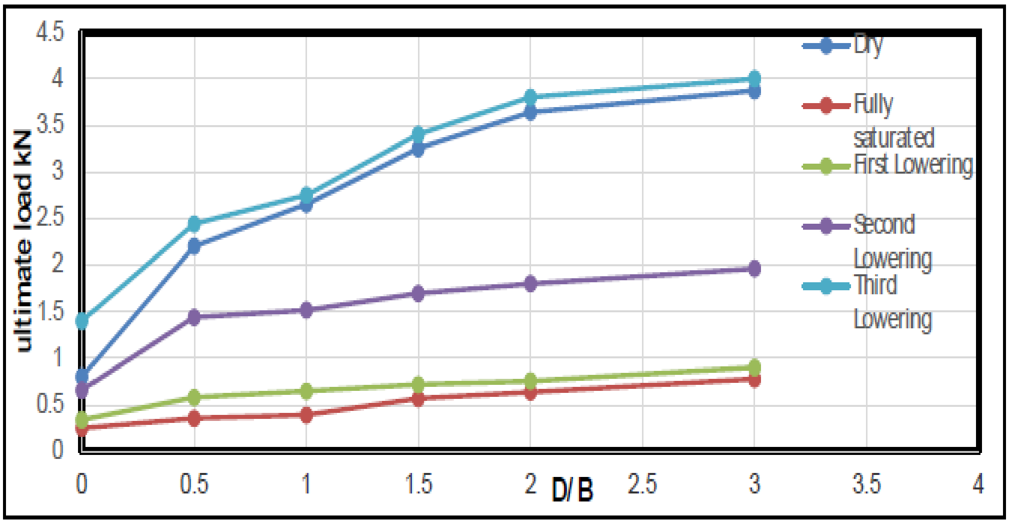


Figure 23: Ultimate load versus L/B ratio for foundation resting on dry, fully saturated, and partially Saturated loose sand of (Dr=30%) with different values of matric suction

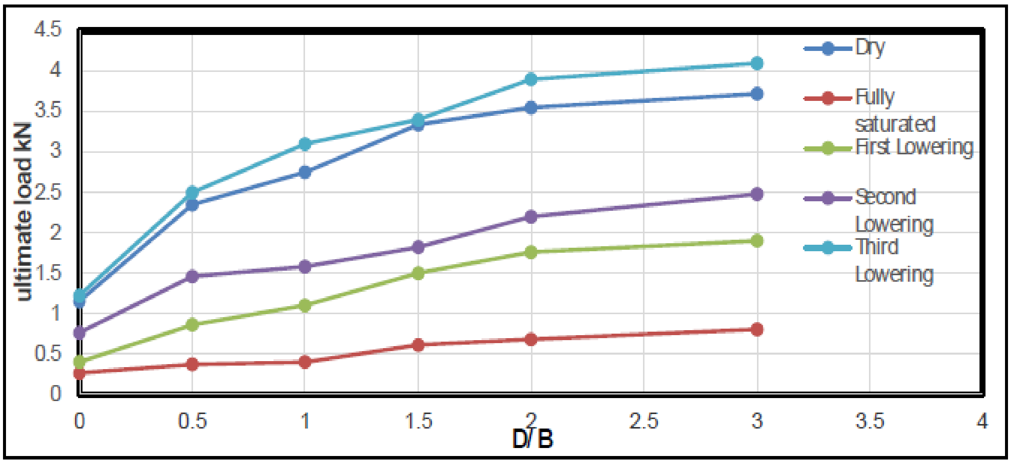


Figure 24: Ultimate load versus D/B ratio for skirt foundation resting on medium dense sand (Dr=50%) of different saturation conditions

Table 5: Ultimate load-carrying capacity values of skirted foundation resting on cohesion less soils of different saturation conditions

Relative density	D/B	Ultimate load carrying capacity (kPa)				
		Fully Sat State	***Dry State***	***Unsat. State 1st lowering***	***Unsat. State 2nd lowering***	***Unsat. State 3rd lowering***
Loose Sand	0	12.5	40	17	33	70
	0.5	17.5	110	29	71.9	122
	1	19.5	132.5	32.4	75	137.5
	1.5	28.4	162.5	35.9	84.8	175
	2	31.9	170	37.8	90	195
	3	38.5	180	41.15	98.1	200
Medium Sand	0	13.1	57.5	20	38	61
	0.5	18.5	117.5	43	73	125
	1	20.1	136	55	79	155
	1.5	30.5	167	75	91	180
	2	34	177.5	88	110	195
	3	40.2	186	95	124	205
Dense Sand	0	17	62.5	40.5	58.5	99
	0.5	39.9	142.5	75	131.5	180
	1	44	157.5	80	140.5	195
	1.5	60	187.5	86.8	148	210
	2	64.5	192.5	91.3	155	215
	3	72.5	202.5	95	160	220

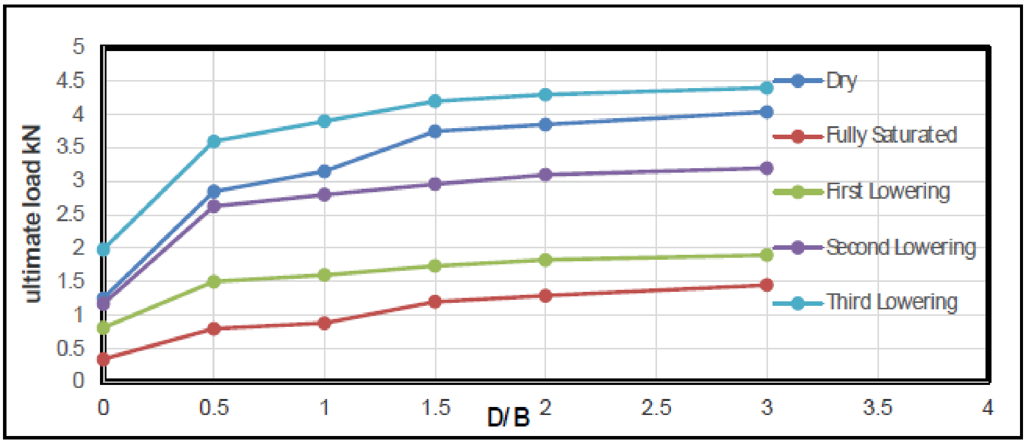


Figure 25: Ultimate load versus D/B ratio for skirt foundation resting on dense sand (Dr=70%) of different Saturation conditions

3.6 Improvement Ratios

Table (6) shows the values of the increment ratio of ultimate carrying capacities of skirt foundation models for different D/B ratios and saturation conditions compared to fully saturated soil. The results show that the increment ratios of the bearing capacity increase with increasing suction values and even more than that of dry conditions for a matric suction value of 9.6 kPa. This is, as mentioned before, due to attraction forces introduced when lowering the water table in the cohesion of fewer soils. Table (6) shows the increment ratio in the bearing capacity of skirt models due to different saturation conditions of partially saturated soils times fully saturation conditions.

Table 6: Increment ratios of the ultimate load-carrying capacity of skirted foundation models for different D/B ratios and saturation conditions compared to fully saturated soil

Relative density	D/B	The Improvement ratios in Ultimate load carrying capacity			
		Dry State	*Unset. State 1st lowering*	*Unset. State 2nd lowering*	*Unset. State 3rd lowering*
Loose Sand	0	3.2	1.36	2.64	5.6
	0.5	6.21	1.63	4.06	6.89
	1	7.5	1.66	3.84	7.05
	1.5	5.72	1.26	2.98	6.16
	2	5.32	1.18	2.91	6.11
	3	4.67	1.06	2.54	5.19
Medium Sand	0	4.38	1.52	2.90	4.65
	0.5	6.35	2.32	3.94	6.75
	1	6.67	2.68	3.95	7.71
	1.5	5.47	2.45	2.98	5.90
	2	5.22	2.58	3.23	5.73
	3	4.62	2.36	3.08	5.09
Dense Sand	0	3.67	2.38	3.44	5.82
	0.5	3.57	1.87	3.29	4.51
	1	3.57	1.81	3.1	4.43
	1.5	3.12	1.44	2.46	3.5
	2	2.90	1.41	2.4	3.33
	3	2.79	1.31	2.2	3.03

4. Conclusions

1) A structural skirt increases the bearing capacity, reduces the settlement, and modifies the load settlement behavior of the footing.
2) The results and interpretations presented in the study showed that the ultimate bearing capacity increases with increasing the depth of the skirt in all saturation condition cases of sand at different relative densities.
3) Compared with the dry state, there is a significant decrease in the load-carrying capacity as the soil below the base of the foundation gets fully saturated.
4) In the case of unsaturated soil, the soil bearing values are higher at a higher matric suction than in dry and fully saturated soil cases.
5) In the two cases of lower matric suction, the soil bearing values are lower than dry soil and higher than fully saturated soil.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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