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The Effect of Lateral Confinement on The Ultimate Bearing Capacity of Shallow Foundations on Sand

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The main objective of the present research is to study the effect of using confining system to improve the bearing capacity of the supporting soil. The effects of increasing subgrade stiffness using confining walls on the foundation subgrade and the structure stability are investigated. This practice is investigated numerically using three-dimensional finite element analysis (Plaxis3D). A square foundation subjected to uniform applied stress is idealized with and without confining walls. Based on the results of the numerical analysis, charts are used to evaluate the enhanced bearing capacity of square foundations resting on extended sand, sand relative density, rigid confining walls depth, maximum deformation of the foundation. Moreover, it was observed, for the study variables considered that the bearing capacity can be improved to 3.8 times by laterally confining the soil subgrade. The level of improvement is directly proportional with confining wall depth to foundation width ratio and reversely proportional with sand relative density. However, the capacity is less sensitive to the foundation embedment depth.

1. Introduction

Geotechnical engineers are in challenge to find alternative methods for enhancing the bearing capacity of soil and reducing the settlement of foundations. One of these methods is structural skirts which are defined as embedded walls confining the soil subgrade beneath the foundation. These skirts enhance the foundation performance, including an improvement in settlement reduction and bearing capacity.

Skirted foundations were first used in early 1970's as a supporting unit for floating structures in offshore hydrocarbon projects because of their ease and short time of installation compared with deep foundations such as piers and piles.

In 2003, a study was performed on small scale models of shallow strip foundations with structural skirts on dense sand subjected to central vertical loading, [1]. and the results proved that structural skirts enhance bearing capacity ratio in the range 1.5 to 3.9, depending on the particular geometric and loading conditions.

Experimental study was performed on small scale models on the case of circular footing rested on dry sand and confined by cells with very smooth surfaces, [2]. and it was concluded that the soil ultimate capacity increased 17 times as compared to the unconfined case. Also, that, the cell-sand-footing system acts as a deep foundation (settle together) and the failure takes place as a shear failure in the surrounding soil. While at the large diameter confining cells relative to footing size, the cell-sand-footing system acts at the beginning as one unit but as the failure reaches, the footing only settles while the cell seems to be unaffected. The enhancement according to the experiments is dependent on the (confining cell diameter/footing diameter Ratio).

The performance of shallow foundations confined laterally was studied by many researches utilizing physical and numerical modeling, [3,4,18]. The sand lateral confinement is concluded to improve the foundation bearing capacity because of wall existence. The level of enhancement is directly proportional with wall depth to foundation width ratio and decreasing sand relative density.

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However, the capacity is insensitive to the foundation embedment depth. Skirted foundations are successfully applied as an appropriate alternate to pile, pier and surface foundations for offshore works, jacket structures, oil platforms and wind turbines as shown in Figures 1 (a) & (b). The main advantages of skirted foundations compared with conventional deep foundations are their easy and short time of installation and economic efficiency.

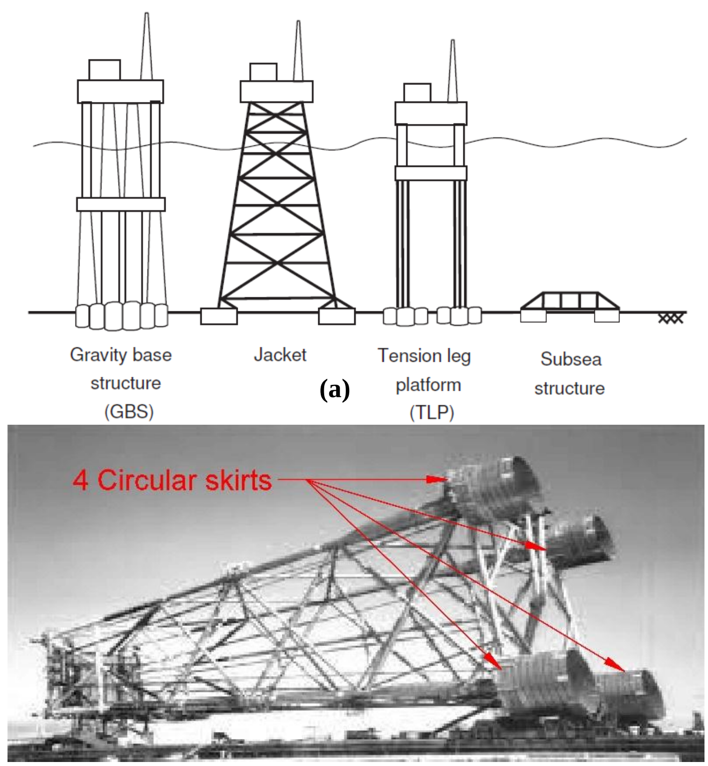


Figure 1:a) & b) Applications of offshore skirted foundations [5]

This paper aims to study the change in behavior of shallow foundations because of lateral confinement of the bearing sand as well as the failure mechanism. 3D Numerical modeling (PLAXIS) was utilized for this aim. The models were formed to simulate square foundations that are confined by skirted walls to bear excavation sides of loose or dense sand as shown in Figure 2.

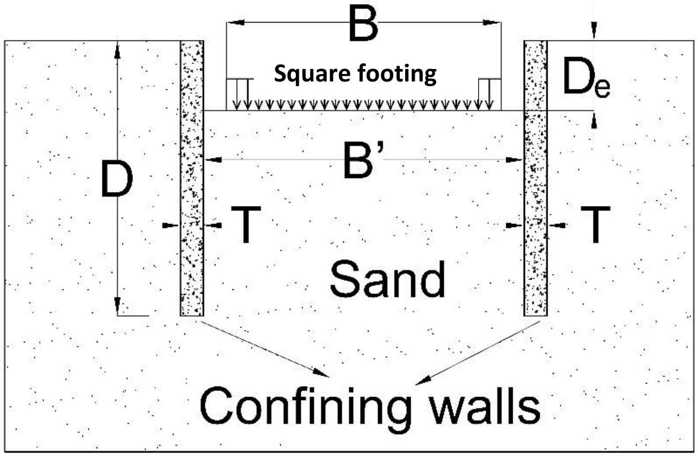


Figure 2: Foundation – Confining walls system model

2. Modelling and Methodology

According to the aforementioned researches, [3,4,18], that the soil confinement effect changes according to the relative density of the soil, so, the soil is categorized into loose and dense sand. The input of the material parameters according to the model used is given in Table 1.

Where B is the foundation width, B' is the confining width, T is the confining walls thickness, D is the confining depth, De is the foundation embedment depth and B', T, D & De are all functions of B.

2.1. PLAXIS idealization

The finite element program used is PLAXIS 3D version20 which is released by Bentley in 2019 [9].

The confining walls are modelled as rigid concrete volume. The material properties of the concrete are shown in Table 1.

Table 1: Material properties of the concrete

parameter		Concrete	Unit
Material model		Linear-elastic	
Drainage type		Non-porous	
Concrete unit weight	γ_{unsat}	24	KN/m^3
Young's modulus	$E^{'}$	$26 * 10^6$	KN/m^2
Poisson's ratio	υ'	0.2	-
Interface Strength		Rigid	

The soil is obeying the Mohr-Coulomb material model (MC). and the soil parameters values input is shown in Table 2.

Table 2: Material properties of the soil

parameter		Loose sand	Dense sand	Unit
General				
Material model		Mohr columb	Mohr columb	
Drainage type		Drained	Drained	
Soil unit weight	γ_{unsat}	17	20	KN/m^3
Initial void ratio	e_{init}	0.7	0.4	-
Parameters				
Young's modulus	$E^{'}$	17000	50000	KN/m^2
Poisson's ratio	μ	0.3	0.35	-
Cohesion	C'_{ref}	0	0	KN/m^2
Friction angle	φ'	30	40	°
Dilatancy angle	ψ	10	10	°
Interface				
Strength		Rigid	Rigid	

2.2. Methodology

In order to simplify the analysis of the lateral confinement and to make sure the investigation is studied without the effect of any other factors, the applied loads to the foundation were created as surface pure loads to the foundation by the tool " Surface prescribed displacement ", which is the best simulation for the stress-settlement curve, because it simulates the load increase till it reaches the desired settlement or failure.

There is a general method for evaluating bearing capacity values out of finite element programs which is the stress-settlement curve.

In 2017, Hlina Belachew evaluated the ultimate bearing capacity from finite element analysis, [10]. which showed most adequate way is the stress-settlement curve. There are three major cases of the stress-settlement curves as shown in Figure 3.

The ultimate stress is the point in the stress-settlement curve where the settlement tends to be infinite as in Figure 3. In case (a) the curve turns vertical at failure where the value of the ultimate bearing capacity. In case (b) the curve turns to semi-vertical at failure, two tangents are drawn from the first and end points on the curve. The intersection of the two tangents determines the ultimate bearing capacity. In case (c) the curve is semi - linear and there is no sign of failure, in this case there are values of the settlement at ultimate failure stress mentioned in Table 3, and the ultimate bearing capacity is the corresponding value to the settlement value, as an example, a footing width of 6m, according to table 3 the settlement at ultimate stress is 5% of footing width which is equal 0.3m. So. The stress value at the stress-settlement curve Figure3c is equal to the ultimate stress which correspond to 0.3m settlement.

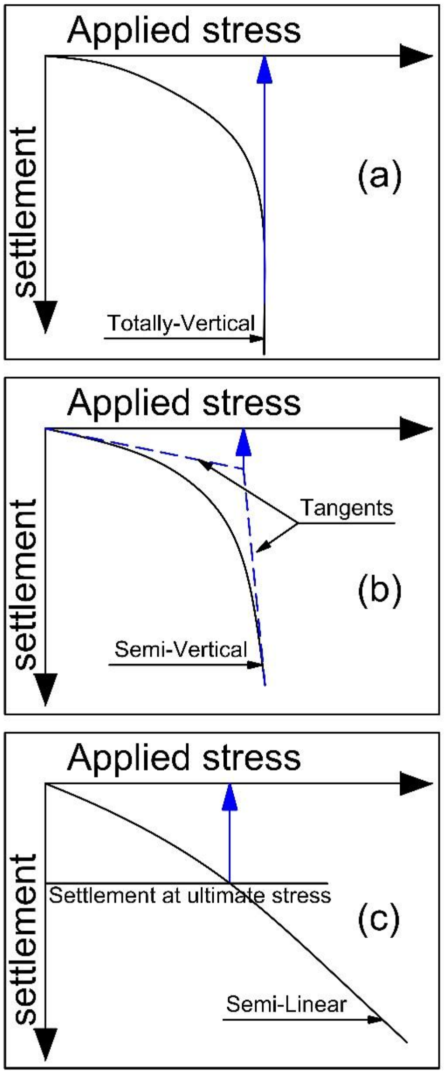


Figure 3: Evaluating of Ultimate bearing capacity from Stress-settlement curves

Table 3: Settlement of the foundation at ultimate stress [11]

Soil	D_e/B Foundation Embedment depth/ Foundation width	S_u/B % Settlement at Ultimate stress/ Foundation width
Sand	0	5 to 12
	Large	25 to 28
Clay	0	4 to 8
	Large	15 to 20

2.3. Parametric study scheme

The models and the parametric study scheme is detailed in Table 4.

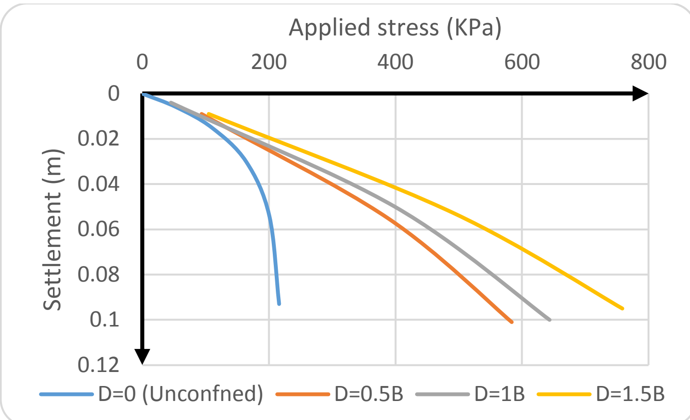
Case No.	Constant Parameters: Relative density	Found. Width (B) (meter)	Confining width (B')	Conf. walls thick. (T)	Conf. walls depth (D)	Foundation embedment depth (De)	Variable Parameters: Variable parameter	1st value	2nd value	3rd value
No.1	Loose	2	1.25B=2.5	0.125B=0.25	Variable (0-0.5B-1.0B-1.5B)	De=0(D) Surface	Confining walls depth (D)	0.50B=1	1.00B=2	1.50B=3
No.2	Dense									
No.3	Loose	6	1.25B=7.5	0.125B=0.75				0.50B=3	1.00B=6	1.50B=9
No.4	Dense									
No.5	Loose	12	1.25B=15	0.125B=1.50				0.50B=6	1.00B=12	1.50B=18
No.6	Dense									
No.7	Loose	6	Variable (1B-1.25B-1.5B)	0.125B=0.75	D=1.00B		Confining width (B')	1.00B=6	1.25B=7.5	1.50B=9
No.8	Dense									
No.9	Loose		1.25B=7.5	Variable (0.05B-0.125B-0.2B)			Conf. walls thick. (T)	0.05B=0.3	0.125B=0.75	0.2B=1.2
No.10	Dense									
No.11	Loose		1.25B=7.5	0.125B=0.75		Variable (0-0.25D-0.50D)	Footing embedment depth (De)	De=0(D) Surface	De=0.25D	De=0.5D
No.12	Dense									

Table 4: Parametric study scheme

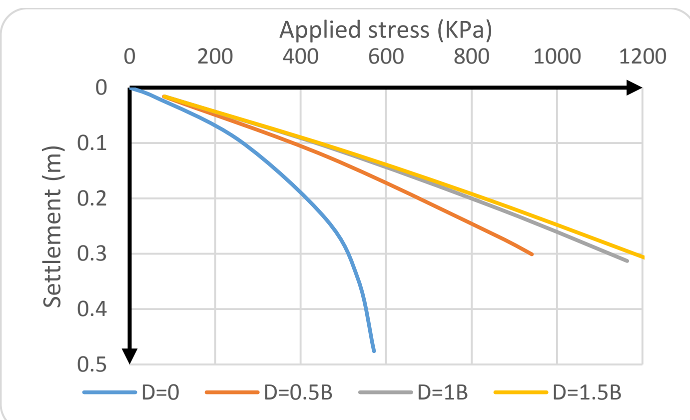
3. Results

3.1. Stress-settlement results

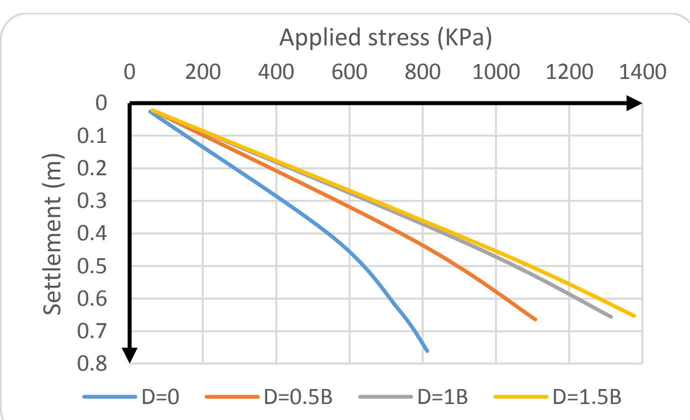
According to Table 4, the results of cases 1 to 12 are shown below, at the x-axis, the uniform stress is applied till failure, while at the y-axis the settlement at center of the foundation is presented.



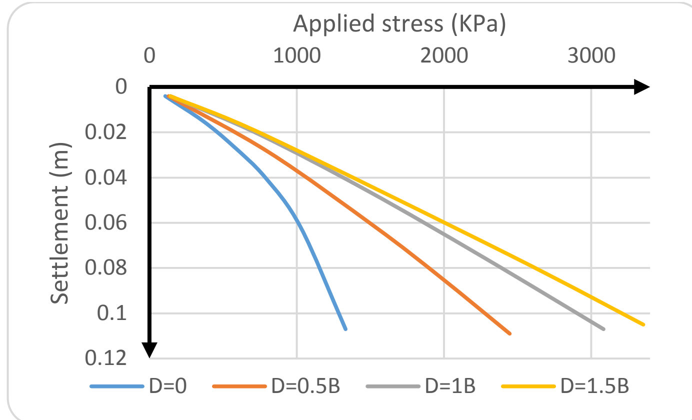
a) Loose sand – Footing width (B) = 2m



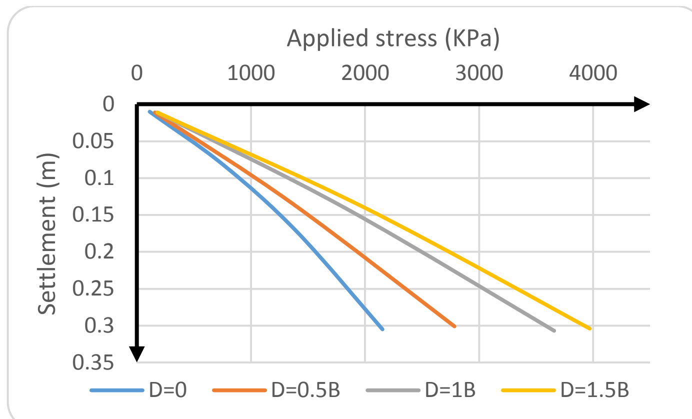
c) Loose sand – Footing width (B) = 6m



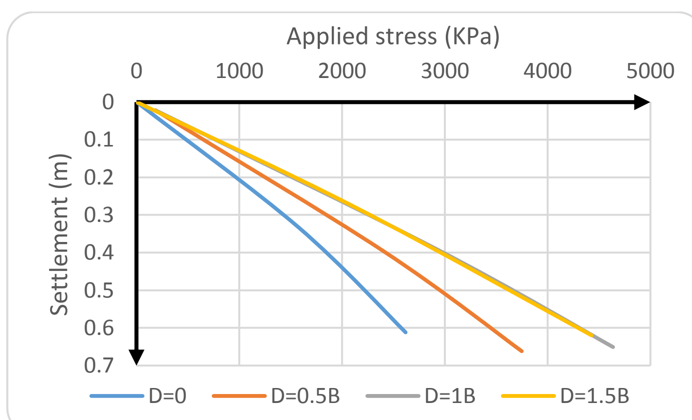
e) Loose sand – Footing width (B) = 12m



b) Dense sand – Footing width (B) = 2m

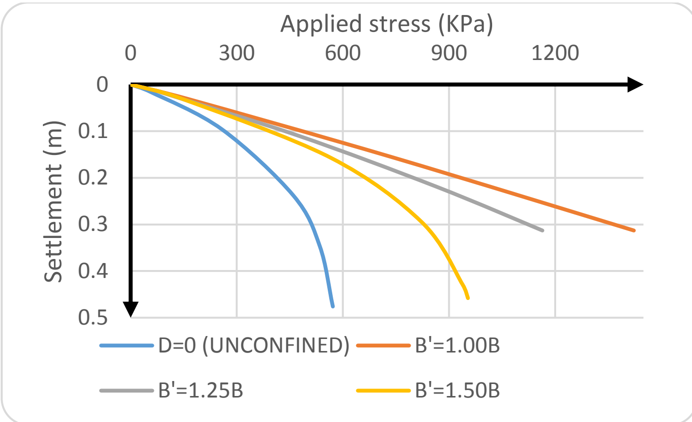


d) Dense sand – Footing width (B) = 6m

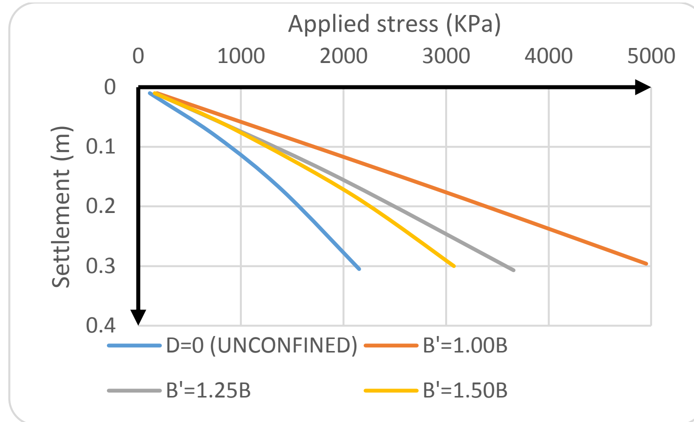


f) Dense sand – Footing width (B) = 12m

Figure 4: Effect of confining walls depth (D) on lateral confinement a & b for B=2m, c & d for B=6m, e & f for B=12m

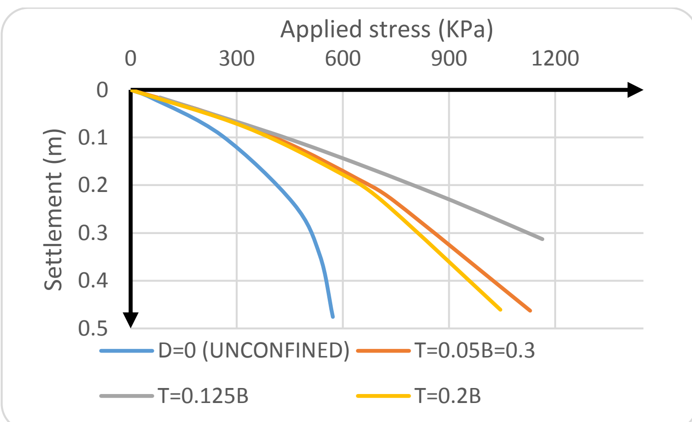


a) Loose sand – Footing width (B) = 6m – Conf. walls depth (D) = 6 m

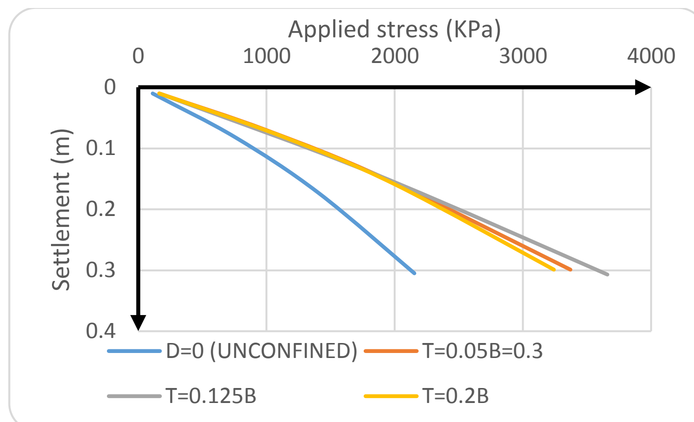


b) Dense sand –Footing width (B)= 6m –Confining walls depth (D)= 6m

Figure 5: Effect of confinement width(B') on lateral confinement

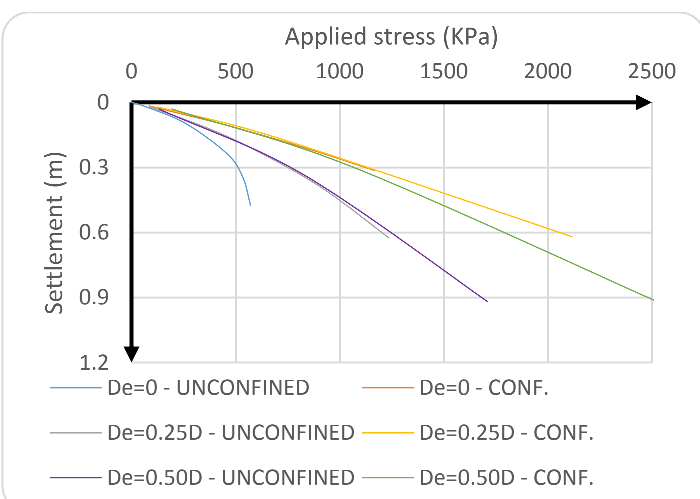


a) Loose sand – Footing width (B) = 6m – Conf. walls depth (D) = 6 m

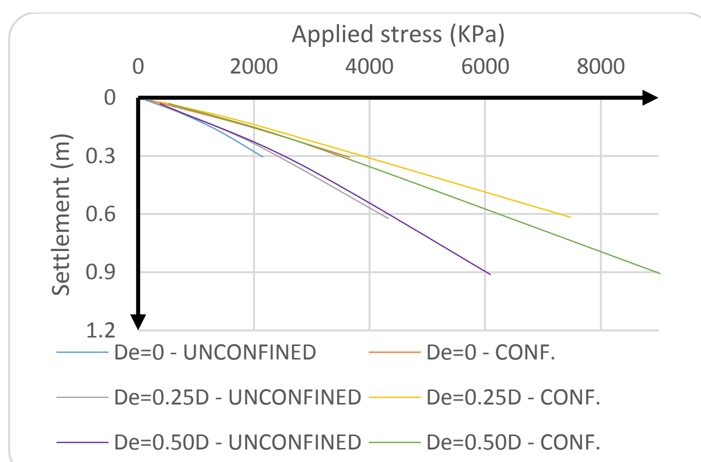


b) Dense sand – Footing width (B)= 6m - Conf. walls depth (D) = 6 m

Figure 6: Effect of confin. walls thick. (T) on lateral confinement



a) Loose sand – Footing width (B) = 6m –Conf. walls depth (D) =6m



b) Dense sand – Footing width (B) = 6m – Conf. walls depth (D) = 6 m

Figure 7: Effect of embedment depth(D_e) on lateral confinement

Figure 4 showed a bigger enhancement of bearing capacity in the loose case than the dense case. Also shows that the confinement system is more effective with less foundation widths.

Figure 5 showed much enhancement with less confinement widths. While Figure 6 showed that the optimum ratio of confining walls thick. Over foundation width is 0.125. Figure 7 showed a negligible effect of embedment depth on the enhancement of bearing capacity.

The ultimate bearing capacity values are summarized in Table 5.

Table 5: Results of Ultimate bearing capacities, qult in kpa

<table>
<tr><th>Case No.</th><th>Relative density</th><th>Foundation width (B)</th><th>Unconfined case (D=0)</th><th colspan="2">1st value</th><th colspan="2">2nd value</th><th colspan="2">3rd value</th></tr>
<tr><td>No.1</td><td>Loose</td><td rowspan="2">2</td><td>200</td><td colspan="2">584</td><td colspan="2">644</td><td colspan="2">759</td></tr>
<tr><td>No.2</td><td>Dense</td><td>1330</td><td colspan="2">2400</td><td colspan="2">2950</td><td colspan="2">3300</td></tr>
<tr><td>No.3</td><td>Loose</td><td rowspan="2">6</td><td>530</td><td colspan="2">940</td><td colspan="2">1100</td><td colspan="2">1200</td></tr>
<tr><td>No.4</td><td>Dense</td><td>2150</td><td colspan="2">2785</td><td colspan="2">3600</td><td colspan="2">3910</td></tr>
<tr><td>No.5</td><td>Loose</td><td rowspan="2">12</td><td>710</td><td colspan="2">1050</td><td colspan="2">1220</td><td colspan="2">1280</td></tr>
<tr><td>No.6</td><td>Dense</td><td>2620</td><td colspan="2">3430</td><td colspan="2">4300</td><td colspan="2">4425</td></tr>
<tr><td>No.7</td><td>Loose</td><td rowspan="6">6</td><td>530</td><td colspan="2">1420</td><td colspan="2">1100</td><td colspan="2">750</td></tr>
<tr><td>No.8</td><td>Dense</td><td>2150</td><td colspan="2">5000</td><td colspan="2">3600</td><td colspan="2">3080</td></tr>
<tr><td>No.9</td><td>Loose</td><td>530</td><td colspan="2">860</td><td colspan="2">1100</td><td colspan="2">810</td></tr>
<tr><td>No.10</td><td>Dense</td><td>2150</td><td colspan="2">3370</td><td colspan="2">3600</td><td colspan="2">3240</td></tr>
<tr><td>No.11</td><td>Loose</td><td></td><td>530</td><td>1100</td><td>1210</td><td>2060</td><td>1690</td><td>2490</td></tr>
<tr><td>No.12</td><td>Dense</td><td></td><td>2150</td><td>3600</td><td>4215</td><td>7310</td><td>6030</td><td>8930</td></tr>
</table>

3.2. Correlation between numerical results and the General equation:

The next table correlates between the ultimate bearing capacity values resulted from PLAXIS 3D and the General equation in the unconfined cases

$$q_u = c' N_c\, F_{cs}\, F_{cd} F_{ci} + qN_q\, F_{qs}\, F_{qd} F_{qi} + \frac{1}{2}\gamma\, BN_\gamma\, F_{\gamma s}\, F_{\gamma d} F_{\gamma i} \quad (1)$$

In this equation:
c' = cohesion
q = effective stress at the level of the bottom of the foundation
γ = unit weight of soil
B = width of foundation
$F_{cs}\ F_{qs}\ F_{\gamma s}$ =shape factors
$F_{cd}\ F_{qd}\ F_{\gamma d}$ = depth factors
$F_{ci}\ F_{qi}\ F_{\gamma i}$ = load inclination factors
$N_c\ N_q\ N_\gamma$ =bearing capacity factors

Table 6: Correlation between numerical and general equation results

<table>
<tr><th rowspan="2">Found. width (B)</th><th rowspan="2">Relative density</th><th rowspan="2">Found. Embedment depth (De)</th><th colspan="2">Ultimate bearing capacity</th><th rowspan="2">% qu Plaxis / qu General equation</th></tr>
<tr><th>General equation</th><th>Plaxis 3D</th></tr>
<tr><td rowspan="2">2</td><td>Loose</td><td rowspan="6">0 (Surface)</td><td>228</td><td>200</td><td>84%</td></tr>
<tr><td>Dense</td><td>1313</td><td>1330</td><td>101%</td></tr>
<tr><td rowspan="2">6</td><td>Loose</td><td>685</td><td>530</td><td>77%</td></tr>
<tr><td>Dense</td><td>3939</td><td>2150</td><td>55%</td></tr>
<tr><td rowspan="2">12</td><td>Loose</td><td>1371</td><td>710</td><td>52%</td></tr>
<tr><td>Dense</td><td>7878</td><td>2510</td><td>32%</td></tr>
<tr><td rowspan="4">6</td><td>Loose</td><td rowspan="2">0.25D = 1.5m</td><td>1479</td><td>1210</td><td>82%</td></tr>
<tr><td>Dense</td><td>7670</td><td>4215</td><td>55%</td></tr>
<tr><td>Loose</td><td rowspan="2">0.5D = 3m</td><td>2379</td><td>1690</td><td>71%</td></tr>
<tr><td>Dense</td><td>11781</td><td>6030</td><td>51%</td></tr>
</table>

According to "Evaluating Bearing Capacity of Layered Soils Using Finite element analysis software by Hlina Belachew in 2017", for an isolated square footing of width 2.5m for different soil types and layers, the percentage of qu PLAXIS 3D over qu General equation ranges from 100% to 67%. So, the results presented in this study by the program are quite reasonable.

3.3. Comparisons and Analysis:

Results of the numerical simulation were analyzed to show the separate effects of sand lateral confinement on the bearing capacity and settlement behavior of shallow foundations. Dimensionless charts for evaluating bearing capacity of confined foundations were formed in terms of the bearing capacity ratios and different affecting parameters.

First parameter is confined foundation width (B), Figure 8 shows the effect of the foundation width (B) on the ultimate bearing capacity ratio of the unconfined case over the confined case.

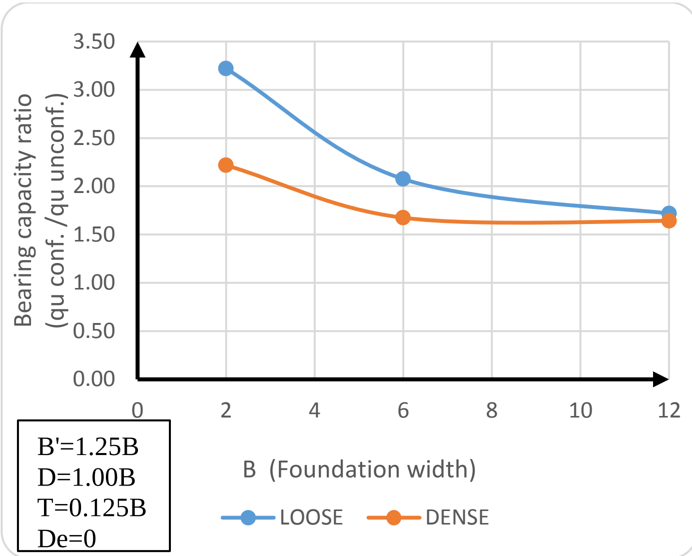


Figure 8: Effect of foundation width on the ultimate bearing-capacity ratio

The foundation Width (B) is reversely proportional with the ultimate bearing capacity ratio (confined case / unconfined case) till 7m width, but it has a less effect on bearing capacity ratio for foundations greater than 7m width

Variation in the bearing capacity ratio of the unconfined case over the confined case, with *D*/*B* values for sand at the different relative densities used in this study are shown in Figure 9 a, b & c. It can be seen that confining wall existence increases bearing capacity of the confined foundation. This improvement is directly proportional to wall depth significantly and reflects the increase in sand confinement in case of higher *D*/*B* values. In addition, the efficiency of such wall existence on improving bearing capacity of foundations increases with decreasing sand relative density.

Relative densities of sand used in this study and those reported in similar researches were used to consider sand shear strengths when forming such charts. Friction forces along the surface area of foundation models were not studied in bearing capacity analyses presented in this research because of their insignificant magnitude compared with the end bearing resistance. This was proved theoretically and experimentally by Byrne (2003) for skirted foundations, [12].

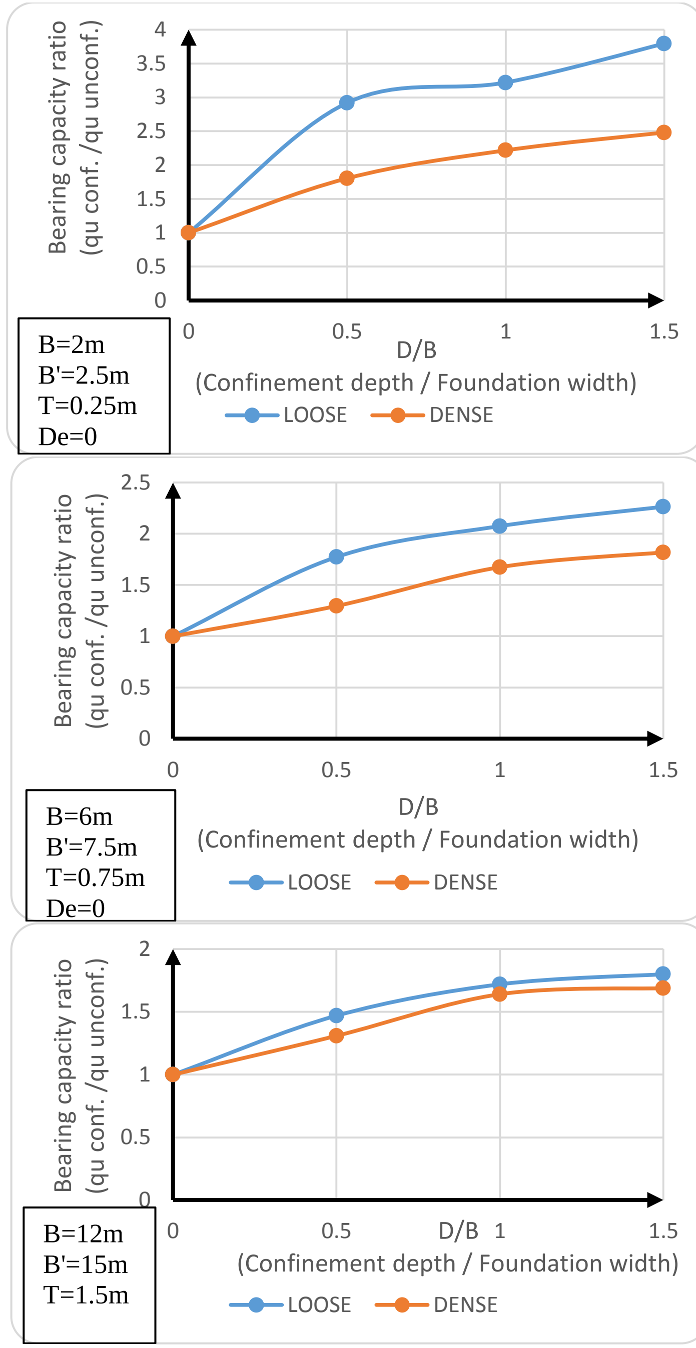


Figure 9: a) B=2m, b) B=6m, c) B=12m,
Effect of confinement depth on the ultimate bearing-capacity ratio

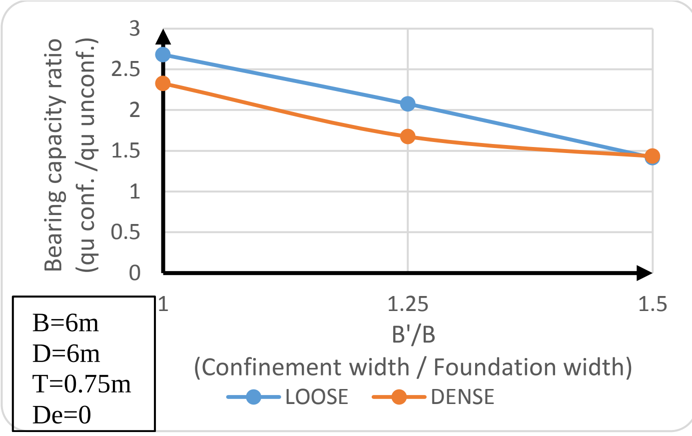


Figure 10: Effect of confinement width on the ultimate bearing-capacity ratio

Third parameter considered is confinement width (B') ranging from 1B to 1.5B as shown in Figure 10. The confining width (B') is better to be equal to the foundation width (B).

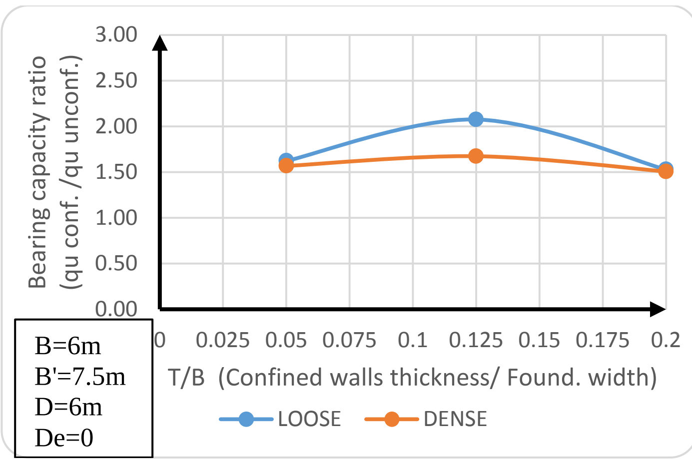


Figure 11: Effect of confining walls thick on the ultimate bearing-capacity ratio

Fourth parameter is the confining walls thickness (T) ranging from 0.05B to 0.2B as shown in figure 11. The optimum ratio of confining walls thickness (T) to confined foundation width (B) is between 0.1 to 0.15 in loose sand, while in dense sand (T) has an insignificant effect on the bearing capacity ratio.

The effect of the embedment depth on bearing capacities of such confined foundations was studied by comparing capacities extracted from testing embedded and surface foundation models of
the same *D*/*B* value. Varying the embedment depth is shown to has an insignificant effect on the evaluated bearing capacities of confined foundations. As shown in Figure 12, this conclusion is strengthened by results from the FEA performed in this study as well as data shown by El Sawwaf and Nazer, [2] for walled, circular foundation models with a B'/B value of 1.33 and De/D values up to 0.67 resting on extended sand and also H.T. Eid, [3], for Comparative study on the behavior of square foundations resting on confined sand. This behavior may be related to having the same overburden pressure for the walled foundations of equal wall depth regardless of the value of the embedded depth, consequently yielding similar estimated bearing capacities.

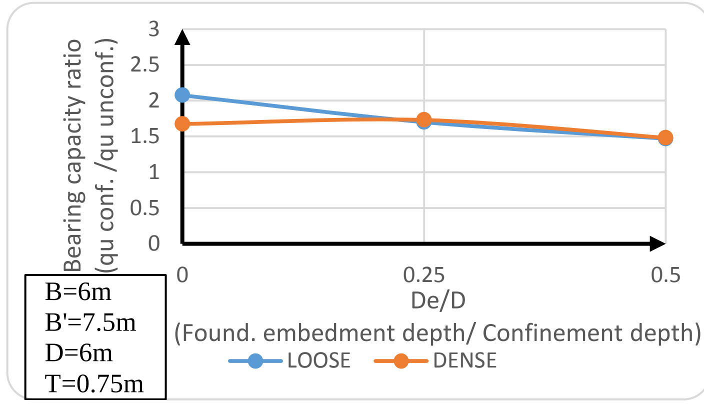


Figure 12: Effect of confining walls thick on the ultimate bearing-capacity ratio

4. Conclusions

Numerical modelling was adopted to study the effect of lateral confinement on the ultimate bearing capacity of the soil, and the following conclusions were drawn:

(1) Sand lateral confinement because of wall existence improves the foundation bearing capacity by a ratio ranges from 1.3 to 3.8 depending on the parameters. The level of improvement is directly proportional with confining wall depth to foundation width ratio and decreasing sand relative density. However, the capacity is less sensitive to the foundation embedment depth.

(2) Bearing capacities of confined foundations can be evaluated in terms of the capacity of a surface foundation on extended sand, sand relative density and confining wall depth to foundation width ratio. Charts were shown to evaluate these capacities.

(3) Existence of the walls can significantly reduce settlement of sand bearing the shallow foundations.

(4) The foundation width (B) is reversely proportional with the ultimate bearing capacity ratio (confined case / unconfined case) till 7m width, but it has a less effect on bearing capacity ratio for foundations greater than 7m width.

(5) The relative density is reversely proportional with the bearing capacity ratio, but it has an insignificant effect on the greater foundation widths from 12m and greater.

(6) The confining depth (D) is directly proportional with the bearing capacity ratio significantly, and its effect shows more with smaller foundations widths.

(7) The confining width (B') is better to be equal to the foundation width (B).

(8) The optimum ratio of confining walls thickness (T) to confined foundation width (B) is between 0.1 to 0.15 in loose sand, while in dense sand (T) has an insignificant effect on the bearing capacity ratio.

(9) The foundation embedment depth has negligible effect on the bearing capacity ratio.

(10) Increasing the depth of the confining walls, results in increasing the surface area of the walls- model footing,

which transfers footing loads to deeper depths and leads to enhancing the bearing capacity ratio.

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