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Bearing capacity of rectangular footing on layered sand under inclined loading

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ABSTRACT

Purpose: The study presents the numerical study to investigate the bearing capacity of the rectangular footing on layered sand (dense over loose) using ABAQUS software.

Design/methodology/approach: Finite element analysis was used in this study to investigate the bearing capacity of the rectangular footing on layered sand and subjected to inclined load. The layered sand was having an upper layer of dense sand of varied thickness (0.25 W to 2.0 W) and lower layer was considered as loose sand of infinite thickness. The various parameters varied were friction angle of the upper dense (41° to 46°) and lower loose (31° to 36°) layer of sand and load inclination (0° to 45°), where W is the width of the rectangular footing.

Findings: As the thickness ratio increased from 0.00 to 2.00, the bearing capacity increased with each load inclination. The highest and lowest bearing capacity was observed at a thickness ratio of 2.00 and 0.00 respectively. The bearing capacity decreased as the load inclination increased from 0° to 45°. The displacement contour shifted toward the centre of the footing and back toward the application of the load as the thickness ratio increased from 0.25 to 1.25 and 1.50 to 2.00, respectively. When the load inclination was increased from 0° to 30°, the bearing capacity was reduced by 54.12 % to 86.96%, and when the load inclination was 45°, the bearing capacity was reduced by 80.95 % to 95.39 %. The results of dimensionless bearing capacity compare favorably with literature with an average deviation of 13.84 %. As the load inclination was changed from 0° to 45°, the displacement contours and failure pattern shifted in the direction of load application, and the depth of influence of the displacement contours and failure pattern below the footing decreased, with the highest and lowest influence observed along the depth corresponding to 0° and 45°, respectively. The vertical settlement underneath the footing decreased as the load inclination increased, and at 45°, the vertical settlement was at its lowest. As the load inclination increased from 0° to 45°, the minimum and maximum extent of influence in the depth of the upper dense sand layer decreased, with the least and highest extent of influence in the range of 0.50 to 0.50 and 1.75 to 2.00 times the width of the rectangular footing, respectively, corresponding to a load inclination of 45° and 0°

Research limitations/implications: The results presented in this paper were based on the numerical study conducted on rectangular footing having length to width ratio of 1.5 and subjected to inclined load. However, further validation of the results presented in this paper, is recommended using experimental study conducted on similar size of rectangular footing.

Practical implications: The proposed numerical study can be an advantage for the civil engineers designing rectangular footings subjected to inclined load and resting on layered (dense over loose) sand.

Originality/value: No numerical study of the bearing capacity of the rectangular footing under inclined loading, especially on layered soil (dense sand over loose sand) as well as the effect of the thickness ratio and depth of the upper sand layer on displacement contours and failure pattern, has been published. Hence, an attempt was made in this article to investigate the same.

Keywords: Rectangular footing, Inclined load, Finite element analysis, Bearing capacity, Layered sand, Thickness ratio, Friction angle of upper and lower sand layers, Load inclination

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ANALYSIS AND MODELLING

1. Introduction

With the support of the footing, the load of the superstructure is transferred to the soil underneath it. A footing can be shallow or deep depending on the depth to width ratio. The load must be transmitted beneath the footing in such a way that it is safe from settlement and shear failure considerations. A large number of studies [1-28] have been published to determine the bearing capacity of footings subjected to vertical or inclined load and resting on single layer or layered soils. Researchers [6, 23] studied the bearing capacity of strip and circular footing on layered soil (dense sand over loose sand). Other researchers [1,5,7,8,11,14,17, 23,24] studied the bearing capacity of the strip, circular and square/rectangular footing on layered soil (dense sand over soft clay). Researchers [21,26] studied the bearing capacity of the strip and rectangular footing on layered soil (stiff clay over loose sand). All the above studies [6,-8,11,14,17,21, 23, 24,26] were conducted under vertical loading. Similarly the researchers [2-4, 15,20] studied the bearing capacity for the strip and circular footing under inclined loading resting on layered soil (dense sand over loose sand; loose sand over dense sand and dense sand over soft clay). Further, different approaches were used by the researchers to study the bearing capacity of the footing. Limit equilibrium approach [1,2,10,11] were used to study the bearing capacity of the strip and circular footing. An equation was proposed by [1,2] for the ultimate bearing capacity for the strip and circular footing on layered soil (dense sand over loose sand) using punching shear coefficient for the vertical as well as for the inclined loading. The results obtained from the study of [1,2] and [10] were compared by [29] and concluded that the result obtained from [1,2] overestimate the bearing capacity at greater depths. Kinematic approach used by [11] to estimate the average pressure below the strip footing. The projected area approach was followed by [10,11,14,17,24] for the strip, circular and square/rectangular footing on layered soil under vertical loading. An equation was proposed by [14,17,24] to predict the ultimate bearing capacity for strip, circular and square/rectangular footing on layered soil (dense sand over soft clay) considering punching shear coefficients, load dispersion angle and soil properties under vertical loading. These studies [14,17,24] overestimated the bearing capacity in comparison to the results reported in previous studies [1,18]. On layered soil (dense sand over loose sand, dense sand over soft clay), finite element modelling was used to determine the bearing capacity of strip and circular [6,21,23,28] and rectangular [26,27] footings (soft clay over dense sand; dense sand over loose sand) under vertical loading. The bearing capacity was found to be dependent on the empirical correlation used to define the soil properties in the above numerical studies. Furthermore, a great deal of research has been done on the strip and circular footing on layered soil (dense sand over loose sand/loose sand over dense sand/dense sand over soft clay/soft clay over dense sand) based on the literature using approaches such as limit equilibrium, kinematic, projected area and finite element method. Since then, no numerical study of the bearing capacity of the rectangular footing under inclined loading, especially on layered soil (dense sand over loose sand) as well as the effect of the thickness ratio and depth of the upper dense sand layer on displacement contours and failure pattern, has been published. As a result, the current study attempted to fill this gap by examining the bearing capacity of a rectangular footing placed on dense sand overlying loose sand under inclined loading using finite element analysis.

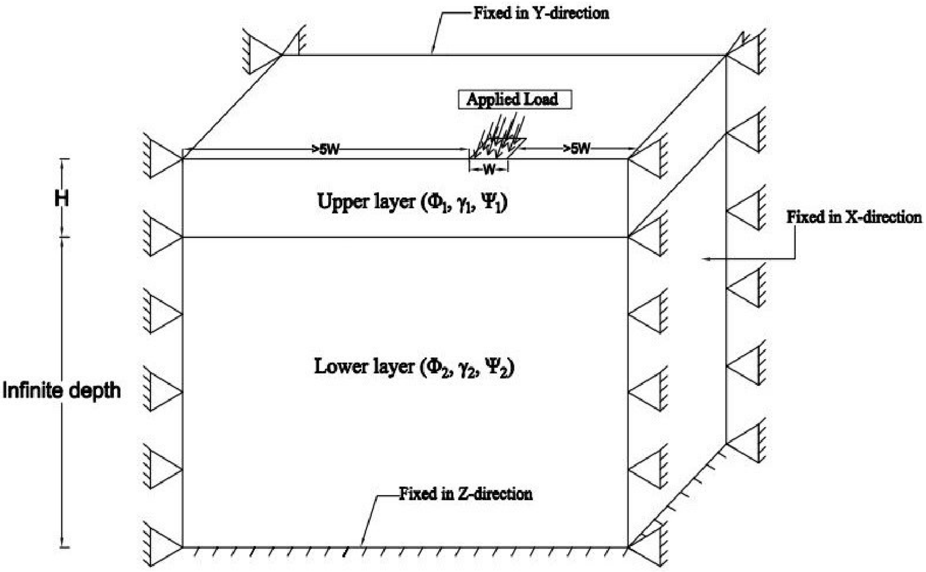


Fig. 1. Problem domain and soil defining parameters

2. Problem definition and soil parameters

An un-symmetric two-layered soil model was constructed, as shown in Figure 1. For the analysis, the rectangular footing of 3 m in length (L) and 2 m in width (W) was considered. In the centre of the rectangular footing, the load was applied at an angle θ. The soil model chosen had a dimension of 33 m along the length and 32 m along the width and 10 m along the depth. A minimum of 10 m (5 times the width of the rectangular footing) space was provided in all directions from the footing's edges in order to avoid boundary effects.

The model was made up of two layers, with the upper layer having a small depth (H) and the lower layer having an infinite depth. The bearing capacity estimate was assumed to be unaffected by the water table. For the upper and lower layers, soil parameters such as unit weight (γ_1, γ_2), soil internal friction angle (φ_1, φ_2), dilation angle (ψ_1, ψ_2), poisons ratio (υ_1, υ_2), and modulus of elasticity (E_1, E_2) with subscript 1 and 2 were used. The unit weight, friction angle, poisons ratio for upper and lower sand layer were taken from [30] which were tabulated in the Table 1 and Table 2. The standard penetration resistance (N) was calculated corresponding to the assumed friction angle for the upper dense and lower loose sand layers as per [31]. Modulus of elasticity and dilation angles for the upper and the lower layer were calculated as per [32] and [33] respectively and were shown in Table 1 and Table 2. The load inclination (θ) was varied from 0° to 45°.

Table 1.
Upper dense sand layer properties used for modelling

Φ_1	γ_1, kN/m^3	E_1, MPa	Ψ_1	υ_1
41°	19.5	68.4	11°	0.30
42°	20.0	74.4	12°	0.28
43°	20.5	82.8	13°	0.26
44°	21.0	91.2	14°	0.24
45°	21.5	102.0	15°	0.22
46°	22.0	120.0	16°	0.20

Table 2.
Lower loose sand layer properties used for modelling

Φ_2	γ_2, kN/m^3	E_2, MPa	Ψ_2	υ_2
31°	14.5	22.8	1°	0.35
32°	15.0	26.4	2°	0.34
33°	15.5	31.2	3°	0.33
34°	16.0	33.6	4°	0.32
35°	16.5	38.4	5°	0.31
36°	17.0	43.2	6°	0.30

3. Finite element meshing

Figure 2 shows the three dimensional finite element model of the two layered soil (dense sand over loose sand). The rectangular footing and the upper dense sand layer were believed to be in rigid contact, allowing the load to be transferred directly to the upper dense sand layer beneath the footing.

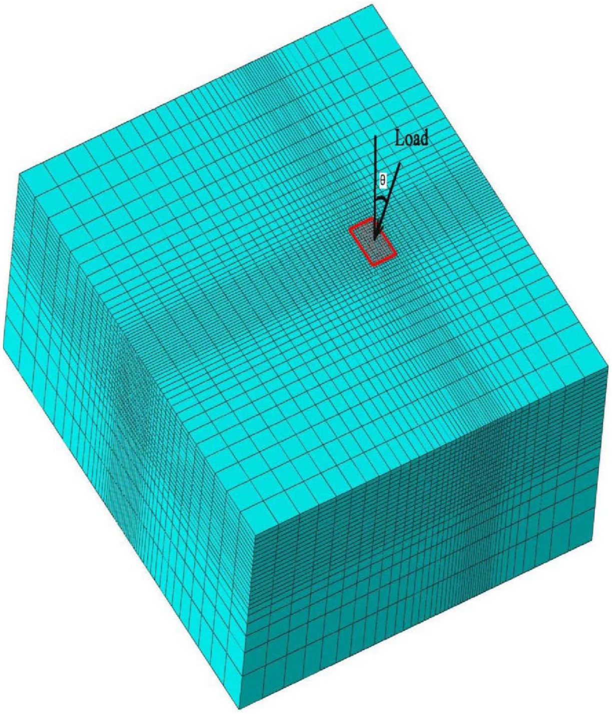


Fig. 2. Meshing of rectangular footing with L/W = 1.5 on layered sand under inclined loading

It's worth noting that [35] reported that the bearing pressure was highest when the L/W ratio was 1.5, after which it began to decrease. As a result, for modelling, a rectangular footing with an L/W ratio of 1.5 was used. It's worth noting that, according to [19], the footing was assumed to be a rigid structure that was only used to transfer the load to the upper dense sand layer. As a result, no actual footing was used in this simulation; instead, the inclined load at an angle θ was applied directly at the centre of the rectangular surface of the upper dense sand layer, as described in [19]. Displacement at all the nodes beneath the rectangular footing was assumed to be constant in the direction of the load application. To compensate for the boundary effect, the distance between the edge of the rectangular footing and the boundary was increased (20 m) in the direction of the applied load compared to the opposite direction (10 m) in order to reduce the simulation time. The model was subjected to a geostatic static stress, which restrains it in all directions to simulate the real soil conditions. The simulation was carried out using the Mohr Coulomb model, which provides a ‘first order' approximation of the sands behaviour by estimating a constant average stiffness and, as a result, reduces simulation time to obtain a first estimate of deformations, whereas other soil hardening models take much longer time [34]. On the model, the mesh was varied, with finer mesh closer to the rectangular footing and coarser mesh as the distance from the footing edge increased. The element used for the modelling was C3D8R. It was discovered that increasing the number of elements in the mesh increased the bearing capacity by 3 to 5%, but the time taken to simulate the same increased by twofold. According to the convergence analysis, the optimum number of elements in the current study was 49393. The bearing capacity of model footings did not change significantly beyond this range.

4. Software validation

The experimental results reported by [3] for the strip footing (L/W = 10) placed on dense sand overlying loose sand under vertical loading were used to validate the ABAQUS software. The strip footing width and the model dimension used for the experimental work were 50 mm and 600 mm x 200 mm x 500 mm respectively. The friction angle of the upper dense and the lower loose sand layer determined through plain strain tests were 47.5° and 34° respectively.

Table 3.
Comparison of the results for the software validation

	Dimensionless bearing capacity ($q_u/\gamma_1 W$)	
H/W	Hanna [3]	Present study
0.00	18.79	16.23
0.25	23.5	22.35
0.50	31.16	28.50
1.00	44.92	58.74

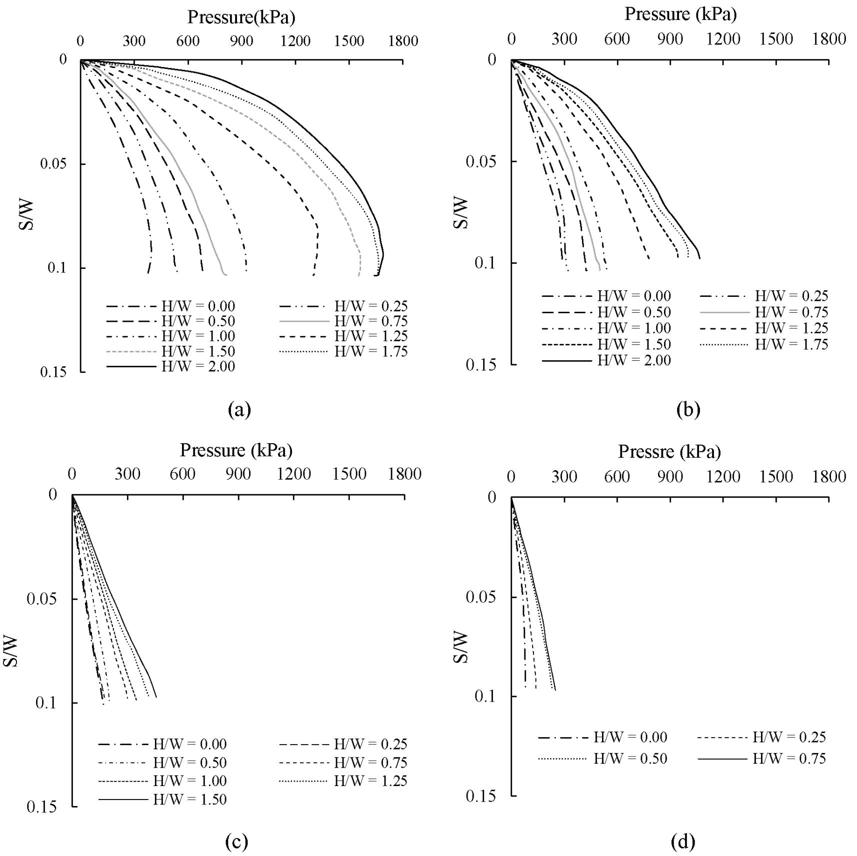
The unit weight of upper dense sand layer and the lower loose sand layer was 16.33 kN/m^3 and 13.78 kN/m^3 respectively. The dimensionless bearing capacity obtained from the numerical study and the one reported by [3] at a varying thickness ratio (H/W) was tabulated in Table 3. Table 3 shows that as the thickness ratio (H/W) increases, the present results were very similar to those of [3], but at the thickness ratio (H/W=1), the present results overestimate those of [3]. The average deviation for the dimensionless bearing capacity was found to be 6.11 %, which could be due to the empirical correlation used to obtain soil defining parameters.

5. Results and discussions

Pressure settlement ratio behaviour

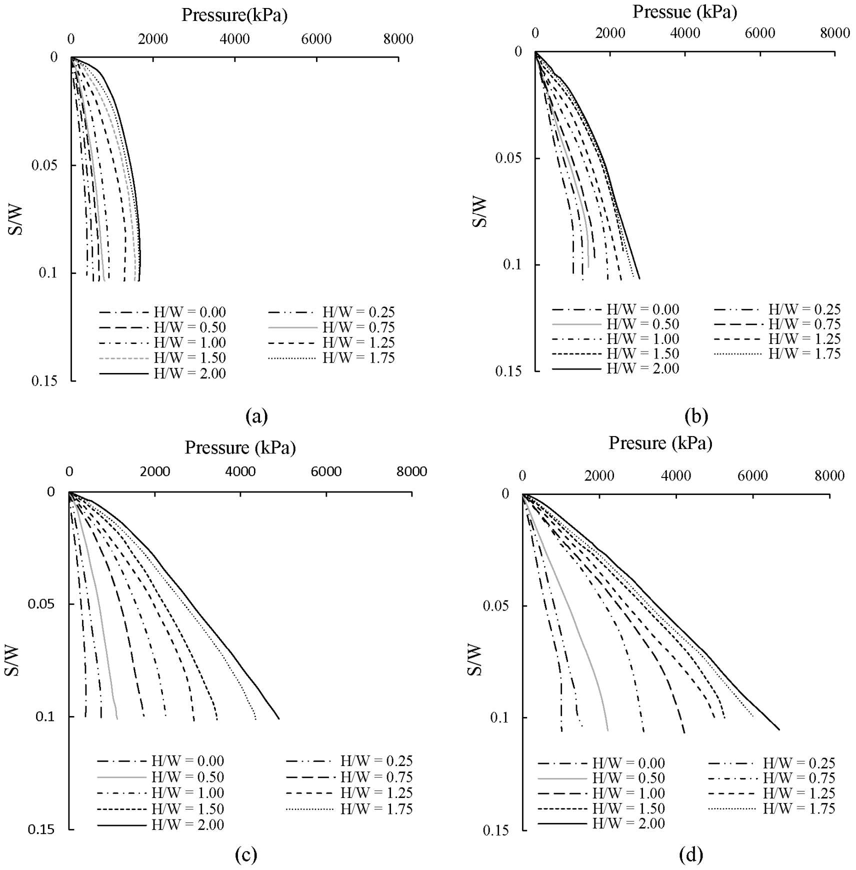
The typical pressure-settlement ratio behaviour obtained from the numerical study corresponding to different thickness ratio (varied from 0.00 to 2), load inclination (varied from 0° to 45°) and friction angles of upper (41°) and lower (36°) sand layers are shown in Figure 3. Figure 4 shows the pressure settlement plots under the vertical load at different combination of friction angles of upper and lower sand layers corresponding to different thickness ratio. It is appropriate to mention here that the bearing capacity corresponding to the peak pressure is taken if the clear peak was observed in the curve. It's worth noting that if the clear peak in the curve is visible, the bearing capacity corresponding to the peak pressure is used. If the peak pressure in the plot could not be found, the bearing capacity was calculated using the minimum of the bearing capacities that corresponded to at least 10% of the settlement ratio or the double tangent method. The numerically obtained bearing capacity for the rectangular footing at different thickness ratio, load inclination and friction angle of lower loose sand layer at φ_1= 41° and φ_2= 31° and φ_1= 46° and φ_2= 36° is tabulated in Table 4. Study of Table 4 reveals, with the increase in thickness ratio from 0.25 to 2.00, the bearing capacity increased for each of the load inclination. This increase in the bearing capacity was attributed to the increase in the thickness of the upper dense sand layer. The highest bearing capacity was observed at a thickness ratio of 2.0 whereas the lowest bearing capacity was corresponding to a thickness ratio of 0.00.

Further examination of Table 4 reveals that the bearing capacity decreased with the increase in the load inclination from 0° to 45°. This decrease in the bearing capacity was attributed to the decrease in the extent of influence due to the load in the upper dense sand layer mobilising less sand to contribute towards bearing capacity. Study of Figure 4 reveals that for the different combinations of friction angles of the upper dense or lower loose sand layer, the bearing capacity increased corresponding to the same thickness ratio for the rectangular footing under vertical loading.



(a) (b) (c) (d)

Fig. 3. Pressure settlement ratio plot for upper dense sand (φ_1) and lower loose sand (φ2) layered soil combination of 41°-31° at (a) 0° (b) 15° (c) 30° (d) 45° load inclination for varying thickness ratio



(a) (b) (c) (d)

Fig. 4. Pressure settlement ratio plot for upper dense sand (φ_1) and lower loose sand (φ_2) layered soil combination of (a) 41°-31° (b) 41°-36° (c) 46°-31° (d) 46°-36° under vertical loading at varying thickness ratio

This increase in the bearing capacity was attributed to the increase in the friction angle of the upper or lower layer of sand. The highest and lowest bearing capacity was observed corresponding to upper dense sand friction angles of 46°-36° and 41°-31° respectively.

Comparison

The experimental results reported by [2] were compared with the results obtained from the present numerical study. The dimensionless bearing capacity obtained from the present numerical study for L/W=1 was calculated and compared with the results reported by [2] for the circular footing as both the footings have similar shape factor. It is pertinent to mention here that [2] used the friction angle and unit weight of the upper dense and lower loose sand layer as 47.5° and 34°, 16.33 kN/m^3 and 13.78 kN/m^3 respectively. The circular footing diameter and the model dimension used for the experimental work were 50 mm and 600 mm x 200 mm x 500 mm respectively. The comparison was shown in Table 5 corresponding to a load inclination (θ) of 0°, 10°, 20° and 30° at a thickness ratio of 1. Study of Table 5 reveals that when the load inclination was increased from 0° to 30°, there was reduction in the bearing capacity of the circular footing by 79.00 % as evident from the results of [2] presented in Table 5. However, in the present numerical study, it was observed from Table 4 that the reduction in the bearing capacity was 54.12% and 81.95% at φ_1= 41° and φ_2= 31° and φ_1= 46° and φ_2= 36° respectively corresponding to a thickness ratio of 1 when the load inclination was increased from 0° to 30°.

This reduction in the bearing capacity reached to about 89.24% and 92.48 % at φ_1= 41° and φ_2= 31° and φ_1= 46° and φ_2= 36° respectively corresponding to same thickness ratio when the load inclination was further increased to 45° as evident from the results tabulated in Table 4. Further examination of Table 4 reveals that the reduction in the bearing capacity was 54.12 % to 86.96% corresponding to different thickness ratio when the load inclination was

Table 4.
Bearing capacity at different thickness ratio, load inclination at φ_1= 41° and φ_2= 31° and φ_1= 46° and φ_2= 36°

φ_1, φ_2	Pressure, kPa					
	H/W	θ = 0°	θ =10°	θ = 20°	θ = 30°	θ = 45°
41°, 31°	0.00	398.43	282.91	239.49	171.16	72.97
	0.25	421.16	300.26	255.13	180.46	80.19
	0.50	548.61	410.22	305.17	200.68	85.06
	0.75	731.59	550.32	398.07	295.6	89.19
	1.00	829.64	600.73	437.4	380.6	89.19
	1.25	1038.76	720.35	515.29	380.6	89.19
	1.50	1305.64	910.73	597.46	380.6	89.19
	1.75	1421.97	980.35	725.44	380.6	89.19
	2.00	1489.23	1000.72	805.47	380.6	89.19
46°, 36°	0.00	1013.48	894.45	487.57	379.71	259.37
	0.25	1441.44	980.31	615.61	411.23	270.64
	0.50	2101.64	1210.16	715.64	479.06	287.06
	0.75	2820.64	1740.68	1040.64	590.46	300.16
	1.00	3995.64	2280.74	1420.56	721.06	300.16
	1.25	4893.16	2710.87	1840.56	850.26	300.16
	1.50	6212.64	3440.96	2310.05	850.26	300.16
	1.75	6432.35	4157.39	2720.87	850.26	300.16
	2.00	6524.59	4480.98	2892.46	850.26	300.16

Table 5.
Comparison of present results for L/W=1 at H/W =1 and φ_1= 46° and φ_2= 34°

Load inclination	Dimensionless bearing capacity ($q_u/\gamma_1 W$)	
	Meyerhof and Hanna [2]	Present study
	φ_1= 47.5° and φ_2= 34°	φ_1= 46° and φ_2= 34°
0°	58.26	52.51
10°	40.49	40.95
20°	26.30	30.84
30°	12.23	17.89

increased from 0° to 30°. This reduction in the bearing pressure increased from 80.95 % to 95.39 % when the load inclination was further increased to 45°. The associated comparison shown in Table 5 suggests that the present results compare favourably with an average deviation of 13.84% in the dimensionless bearing capacity. The difference between the present results and that of [2] is attributed to the size or the scale effect or due to difference in the properties of the upper and lower sand layers used for modelling.

6. Displacement contours and failure pattern under inclined loading

Finite element analysis was performed to study the behaviour of the rectangular footing resting on dense sand overlying loose sand under inclined loading. The soil friction angles for the upper dense (φ_1) and lower loose (φ_2) sand layers were varied from 41° to 46° and 31° to 36° respectively at an interval of 1°. Inclined load was applied at the centre of the rectangular footing which was varied from 0° to 45° for each of the combination investigated. The typical plots for the displacement contours and failure pattern for the friction angle of upper dense and lower loose sand layer of 41° and 36° corresponding to different load inclination and at a thickness ratio (H/W) of 0.25 are shown Figure 5 and Figure 6 respectively. Studies of these figures reveal that at a load inclination of 0°, the displacement contour and failure pattern was symmetrical across the centre of the rectangular footing. With the increase in the load inclination to 15°, 30° and 45°, the displacement contours and failure pattern also moved in the direction of load application. The depth of influence of the displacement contours and failure pattern below the footing decreased as the load inclination increased from 0° to 45°, as shown in

Figures 5 and 6. The greatest influence was observed along the depth at a load inclination of 0°, and the influence reached the surface at a load inclination of 45°. This means vertical settlement was at its lowest, indicating that the bearing capacity of the footing was at its lowest.

6.1. Effect of thickness ratio on the displacement contours and failure pattern under inclined loading

Finite element analysis was performed on the rectangular footing resting on dense sand overlying loose sand. The load was applied at an inclination of 15°. The analysis was performed for the upper dense (γ_1=19.5 kN/m^3) and lower loose (γ_2=14.5 kN/m^3) sand friction angles of φ_1= 41° and φ_2= 31° respectively with thickness ratio (H/W) varying from 0.25 to 2.00. The plots for the displacement contours and failure pattern are shown in Figure 7 and Figure 8, respectively. Study of the Figure 7 shows that with the increase in the thickness ratio (H/W) from 0.25 to 1.25, the displacement contour moved towards the centre of the rectangular footing. When the thickness ratio (H/W) changed from 1.50 to 2.00, the displacement contour moved back toward the application of the inclined load, and the maximum soil displacement was completely contained in the upper dense sand layer, or the rectangular footing's

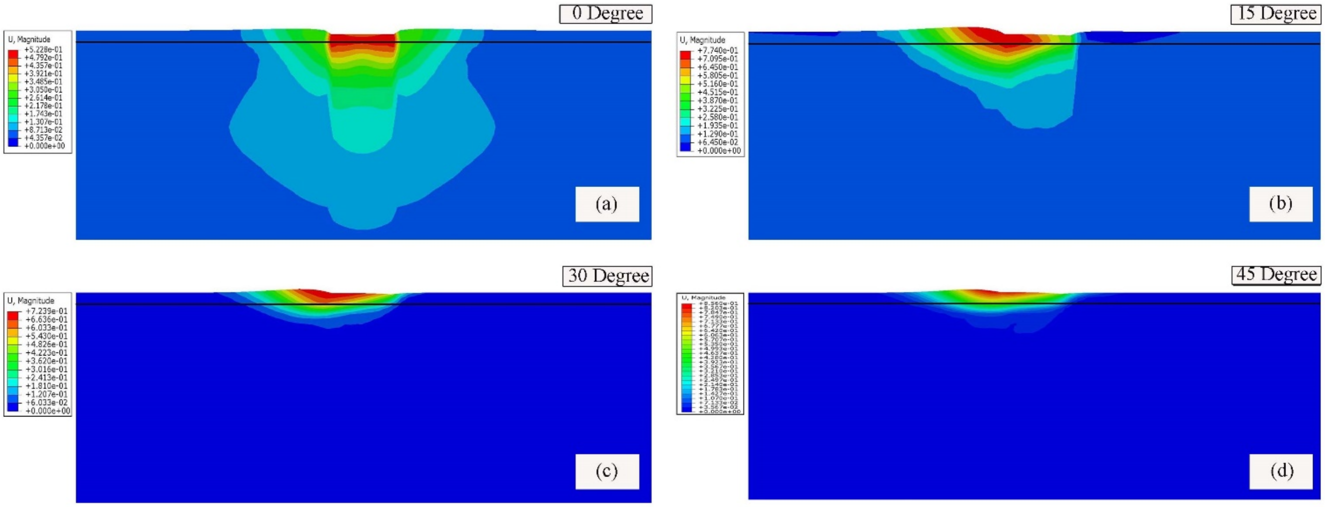


Fig. 5. Displacement contour at thickness ratio 0.25 at φ1=41° and φ2= 36° for different load inclination

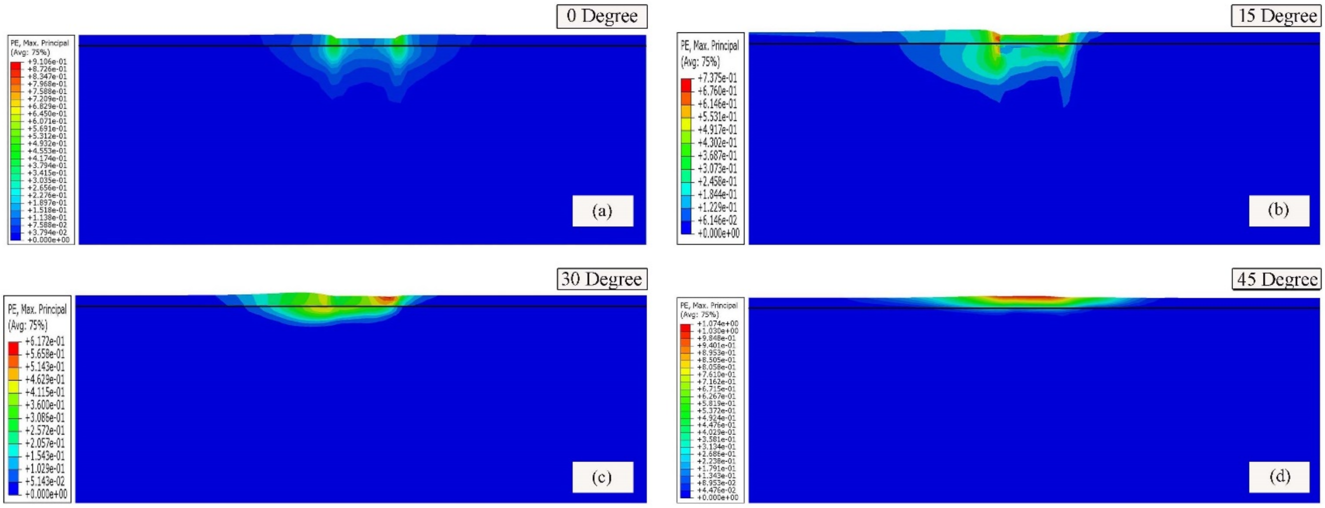


Fig. 6. Failure pattern at thickness ratio 0.25 at φ1=41° and φ2=36° for different load inclination

bearing capacity was completely reliant on the properties of upper dense sand layer. In addition, Figure 8 depicts the failure pattern at a thickness ratios (H/W) ranging from 0.25 to 2.00 using the same soil defining parameter as were used for the displacement contour. It was discovered that the failure pattern depends on the upper and lower sand layers, respectively, as the thickness ratio was increased from 0.25 to 1.25. This means that the bearing capacity of the rectangular footing was governed by the contribution of both the sand layers. The failure pattern shifted entirely to the upper dense sand layer as the thickness ratio (H/W) was increased from 1.5 to 2.00, confirming that the footing's bearing capacity was solely dependent on the properties of the upper dense sand layer.

6.2. Effect of depth of upper sand layer on the displacement contours and failure pattern under inclined loading

Finite element analysis was used to study effect of depth of upper sand layer on the displacement contours and failure pattern under inclined loading. For the upper dense and lower loose sand layers, the friction angles were varied from 41° to 46° and 31° to 36°, respectively. Unit weight of upper

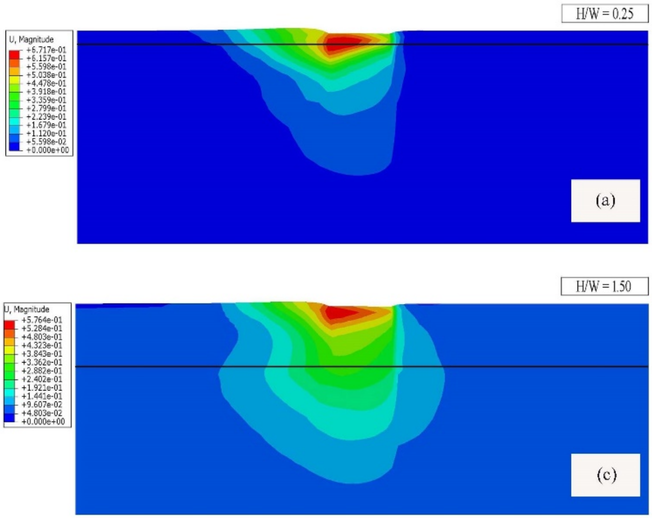


Fig. 7. Displacement contour at a load inclination of 15° at φ1=41° and φ2=31° for different thickness ratio

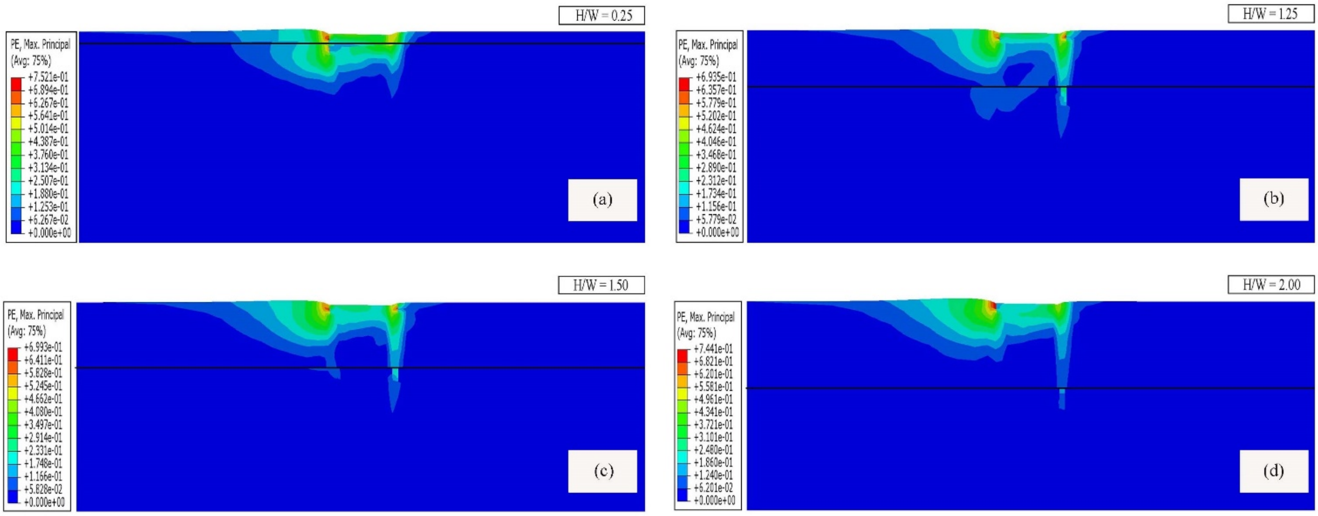


Fig. 8. Failure pattern at a load inclination of 15° at φ_1= 41° and φ_2= 31° for different thickness ratio

dense sand (γ_1) and lower loose sand (γ_2) layer were varied 14.5 kN/m^3 to 17 kN/m^3 and 19.5 kN/m^3 to 22 kN/m^3 respectively at an interval of 0.5 kN/m^3. Inclined load was applied concentrically to the rectangular footing which was varied from 0° to 45° for each of the sand layer combination. Figure 9 and Figure 10 shows the minimum and the maximum extent of influence of the displacement contour and failure pattern in the depth of upper dense sand layer for a load inclination of 0°, 15°, 30° and 45° respectively. Study of Figure 9 and Figure 10 reveals that with the increase in the load inclination from 0° to 45° there was decrease in the minimum and maximum extent of influence in the depth of upper dense sand layer resulting decrease in the bearing capacity. The displacement contour and failure pattern moved in the direction of application of load. The values of minimum and maximum extent of influence in the depth of the upper dense sand layer at varying load inclination was tabulated in the Table 6 which reveals that the minimum and maximum extent of influence in the depth of the upper dense sand layer was observed in the range of 0.50 to 0.50 and 1.75 to 2.00 times width of the rectangular footing corresponding to a load inclination of 45° and 0° respectively. Further, from Table 6, with the increase in the load inclination, the decrease in the extent of influence in the depth of upper dense sand layer was not uniform.

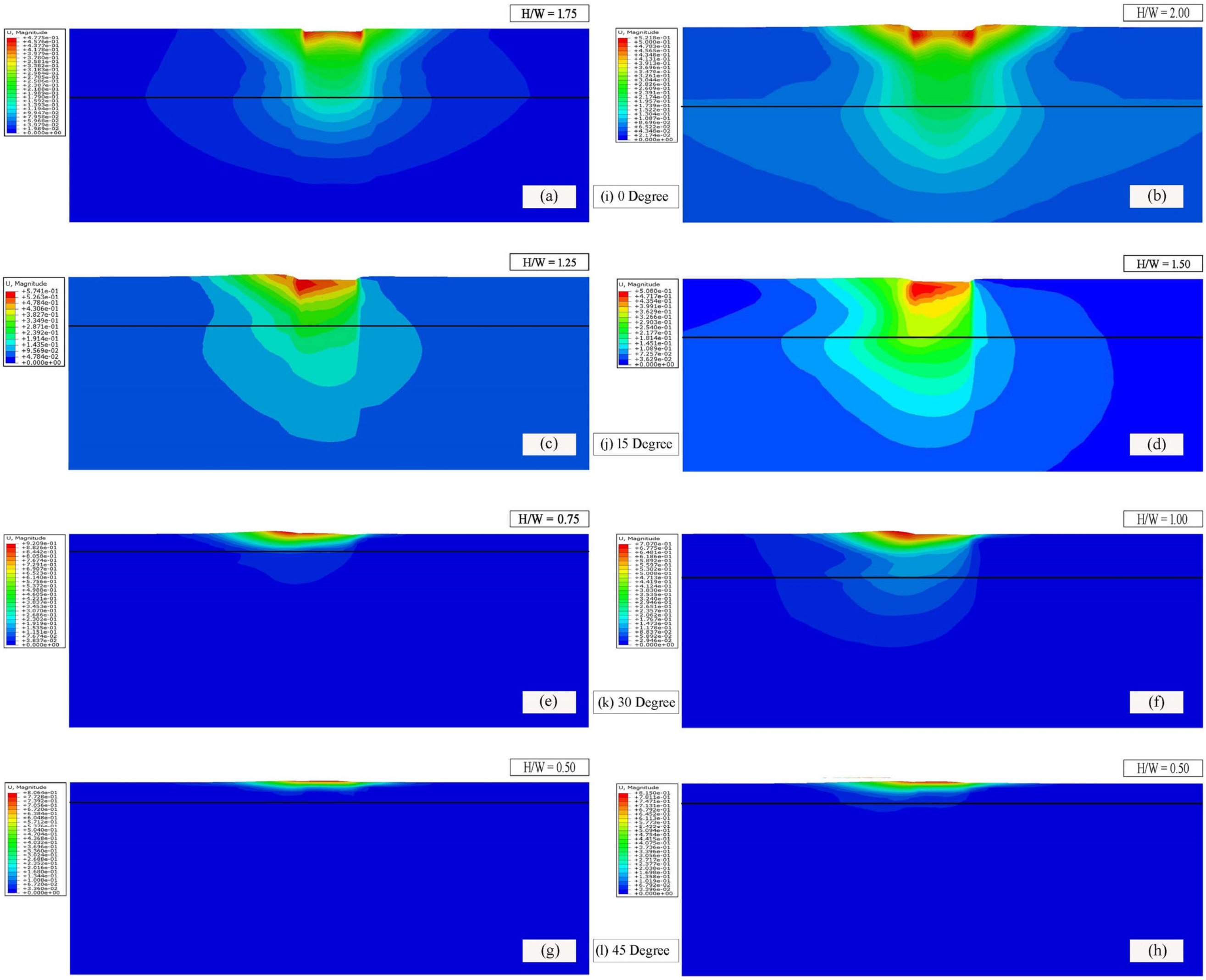
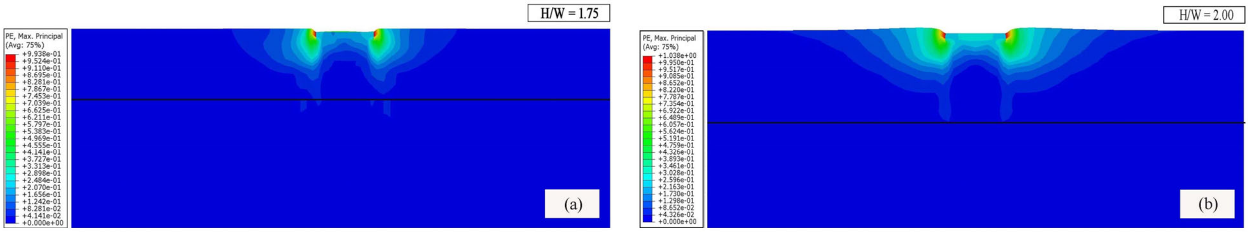
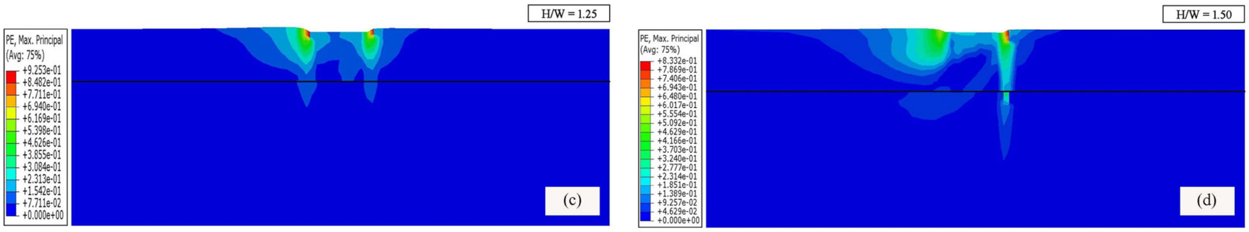


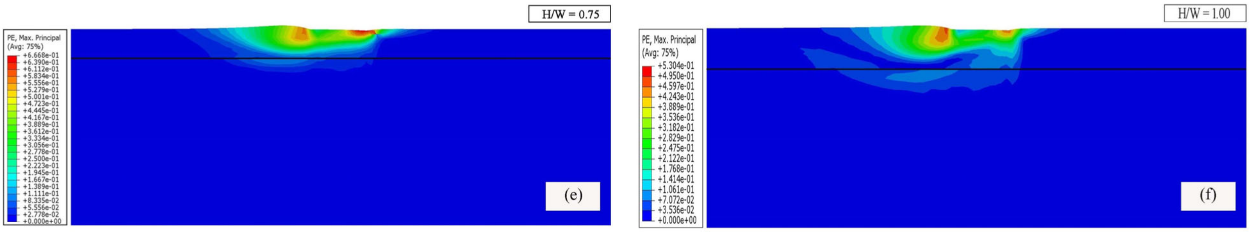
Fig. 9. Minimum and the maximum extent of displacement contour for the extent of influence in the depth of upper dense sand layer at a load inclination of (i) 0° (j) 15° (k) 30° (l) 45°



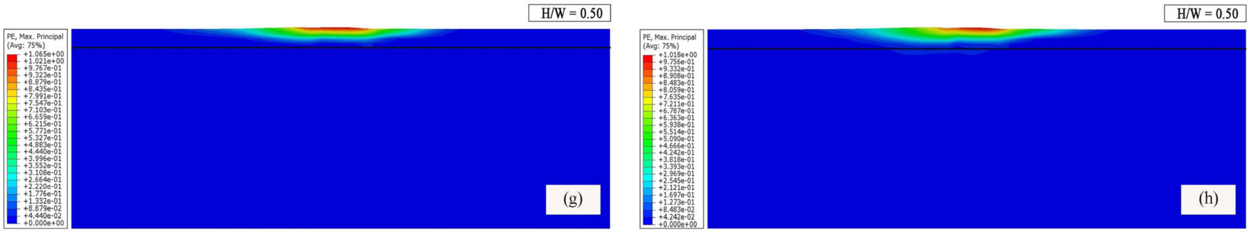
(i) 0 Degree



(j) 15 Degree



(k) 30 Degree



(l) 45 Degree

Fig. 10. Minimum and the maximum extent of failure pattern for the extent of influence in the depth of upper dense sand layer at a load inclination of i) 0° (j) 15° (k) 30° (l) 45°

Table 6.
Minimum and maximum extent of influence in the depth (H) of the upper dense sand layer at varying load inclination

Load inclination, θ	Present study	
	Minimum	Maximum
0°	1.75W	2.00 W
5°	1.50 W	1.75 W
10°	1.25 W	1.75 W
15°	1.25 W	1.50 W
20°	1.00 W	1.50 W
25°	1.00 W	1.25 W
30°	0.75 W	1.00 W
35°	0.75 W	1.00 W
40°	0.50 W	0.75 W
45°	0.50 W	0.50W

7. Conclusions

In this paper a numerical study was performed to investigate the ultimate bearing capacity of the rectangular footing placed on the dense overlying loose sand under inclined loading. The parameters varied were friction angle of the upper dense (41° to 46°) and lower loose (31° to 36°) layer of sand and load inclination (0° to 45°). The following conclusions are put forward:

1. As the thickness ratio increased from 0.00 to 2.00, the bearing capacity increased with each load inclination. The highest and lowest bearing capacity was observed at a thickness ratio of 2.00 and 0.00 respectively. The bearing capacity decreased as the load inclination increased from 0° to 45°.
2. The displacement contour shifted toward the centre of the footing and back toward the application of the load as the thickness ratio increased from 0.25 to 1.25 and 1.50 to 2.00, respectively.
3. When the load inclination was increased from 0° to 30°, the bearing capacity was reduced by 54.12 % to 86.96%, and when the load inclination was 45°, the bearing capacity was reduced by about 80.95 % to 95.39 %.
4. The present results of dimensionless bearing capacity compare favourably with literature with an average deviation of 13.84 %.As the load inclination was changed from 0° to 45°, the displacement contours and failure pattern shifted in the direction of load application, and the depth of influence of the displacement contours and failure pattern below the footing decreased, with the highest and lowest influence observed along the depth corresponding to 0° and 45°, respectively.
5. The vertical settlement underneath the footing decreased as the load inclination increased, and at 45°, the vertical settlement was at its lowest.
6. As the load inclination increased from 0° to 45°, the minimum and maximum extent of influence in the depth of the upper dense sand layer decreased, with the least and highest extent of influence in the range of 0.50 to 0.50 and 1.75 to 2.00 times the width of the rectangular footing, respectively, corresponding to a load inclination of 45° and 0°.

The results presented in this paper were based on the numerical study conducted on rectangular footing having length to width ratio of 1.5 and subjected to inclined load. However, further validation of the results presented in this paper, is recommended using experimental study conducted on similar size of rectangular footing. The proposed numerical study can be an advantage for the civil engineers designing rectangular footings subjected to inclined load and resting on layered (dense over loose) sand.

Notations

φ_1, φ_2	Friction angle for upper dense and lower loose sand
γ_1, γ_2	Unit weight of the upper dense and lower loose sand
E_1,E_2	Elastic moduli for upper dense and lower loose sand layer
υ_1, υ_2	Poisons ratio for upper dense and lower loose sand layer
W	Width of the rectangular footing
L	Length of the rectangular footing
θ	Load inclination with respect to vertical
S/W	Settlement ratio
q_u	Ultimate bearing capacity
H	Thickness of the upper dense sand layer
H/W	Thickness ratio

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