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Numerical study of ultimate bearing capacity of rectangular footing on layered sand

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ABSTRACT

Purpose: The purpose of this study is to investigate the ultimate bearing capacity of the rectangular footing resting over layered sand using finite element method.

Design/methodology/approach: Finite element analysis was used to investigate the dimensionless ultimate bearing capacity of the rectangular footing resting on a limited thickness of upper dense sand layer overlying limitless thickness of lower loose sand layer. The friction angle of the upper dense sand layer was varied from 41° to 46° whereas for the lower loose sand layer it was varied from 31° to 36°.

Findings: The results reveal that the dimensionless ultimate bearing capacity was found to increase up to an H/W ratio of about 1.75 beyond which the increase was marginal. The results further reveal that the dimensionless ultimate bearing capacity was the maximum for the upper dense and lower loose sand friction angles of 46° and 36°, while it was the lowest for the upper dense and lower loose sands corresponding to the friction angle of 41° and 31°. For H/W = 0.5 and 2, the dimensionless bearing capacity decreases with the increase in the L/W ratio from 0.5 to 6 beyond which the dimensionless ultimate bearing capacity remains constant for all combinations of parameters. The results were presented in non-dimensional manner and compared with the previous studies available in literature.

Research limitations/implications: The analysis is performed using a ABAQUS 2017 software. The limitation of this study is that only finite element analysis is performed without conducting any experiments in the laboratory. Further the study is conducted only for the vertical loading.

Practical implications: This proposed numerical study can be used to predict the ultimate bearing capacity of the rectangular footing resting on layered sand.

Originality/value: The present study gives idea about the ultimate bearing capacity of rectangular footing when placed on layered sand (dense sand over loose sand) as well as the effect of thickness of top dense sand layer on the ultimate bearing capacity. The findings could be used to calculate the ultimate bearing capacity of the rectangular footing on layered sand.

Keywords: Rectangular footing, Finite element analysis, Bearing capacity, Layered sand

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ANALYSIS AND MODELLING

1. Introduction

In the literature, a number of studies have been reported to estimate the bearing capacity of footings such as circular [1-9,10], square [11,12], strip [10, 13-21] and rectangular [22-25] over single and double layered soil. Researchers [2,5,9, 14-18, 22,26] reported the study to determine the bearing capacity of the footing resting over dense sand overlying soft clay. Further, limited studies in literature [2-4, 6,13,19,20,27] for the footings (strip, circular and square) over layered sand are available. The strip and circular footing's bearing capacity was calculated by [2] under inclined load for the cases (1) dense sand layer over soft clay/loose sand, (2) stiff clay layer over soft clay, and (3) loose sand layer over dense sand. The design charts using punching shear mechanism to calculate the bearing capacity of the strip and circular footing placed on a dense sand layer over loose sand strata, as well as a loose sand layer over dense sand strata were developed by [3,4] similar to the work of [2]. The bearing capacity obtained from the proposed simplified analysis was validated by performing strip and circular footing model tests. The results obtained from the theory and model experiments for footings on dense sand over loose sand were compared by [13] with those calculated from the finite element method and reported that, contrary to the experimental results, the use of the finite element method led to an overestimation of bearing capacity. A numerical method for assessing the bearing capacity of footings over layered soil involving a mixture of cohesive and non-cohesive layers based on the limit-equilibrium approach and the triangular block mechanism proposed by [22] and validated the findings for layered soil based on experimental model tests and the finite element method. Researchers [8,19,23] derived an equation for the bearing capacity for strip, circular and square/rectangular footing resting over layered soil. The impact of the thickness of the upper soft clay layer on the bearing capacity of the strip footing resting on the lower layer of dense sand using finite element method was examined by [21] and concluded that the ultimate bearing capacity decreases as the thickness of the upper soft clay layer increases to a critical thickness beyond which the failure pattern remains within the upper soft layer. Scale effect was examined by [6] by changing the size of the square and the circular footings on the ultimate bearing capacity. This study concluded that with increase in size of footing there was an increase in the bearing capacity of the shallow footing. The above literature clearly indicates that majority of the numerical as well as experimental studies were conducted for the strip and for the circular footing on layered soil. The literature further indicated that very few experimental studies were conducted on rectangular footing's ultimate bearing capacity placed on layered soil. But no numerical study has been reported so far for the ultimate bearing capacity of rectangular footing placed on dense sand overlying loose sand layer. So the present study fills up this gap with the objective to obtain the effect of thickness of dense sand layer overlying loose sand layer on the ultimate bearing capacity of the rectangular footing by conducting a numerical study. The results are resented in non-dimensional form and compared with the past work available in the literature.

2. Problem definition and model parameters

In the model description, a rectangular footing subjected to vertical concentric load with a length-to-width ratio (L/W = 1.5) is considered to be placed on the dense sand overlying loose sand. The thickness (H) of the upper dense sand is very small in comparison to the thickness of the lower loose sand layer (infinite depth). The model problem is specified for a variety of soil combinations with unit weight of upper dense sand layer (γ_1) and lower loose sand layer (γ_2), internal soil friction angle of upper (φ_1) and lower (φ_2) sand layer, poison ratio of upper (μ_1) and lower (μ_2) sand layer, elasticity modulus of upper (E_1) and lower (E_2) sand layer and dilation angle of upper (Ψ_1) and lower (Ψ_2) sand layer. The unit weight (γ_1) of the upper dense sand layer and the unit weight (γ_2) of the lower loose sand layer were varied from 19.5 kN/m^3 to 22.0 kN/m^3 and 14.5 kN/m^3 to 17.0 kN/m^3 respectively at an interval of 0.5 kN/m^3. The friction angle (φ_1) of the upper dense sand layer and the friction angle (φ_2) of the lower loose sand layer were varied from 41° to 46° and 31° to 36° respectively at an interval of 1°. Modulus of elasticity for the upper and lower layers of the sand were computed using a formula 1200 (N + 6) kPa as per [28,29]. In this formula, the N stands for standard penetration resistance and its value was taken against the opted value of friction angle as per [30]. The Poisson's ratio for the upper dense sand and lower loose sand layers were varied from 0.3 to 0.35 and 0.2 to 0.3 as per [28] respectively. The dilation angle for both the layers of the sand was calculated as φ-30° as per [31] for the finite element analysis.

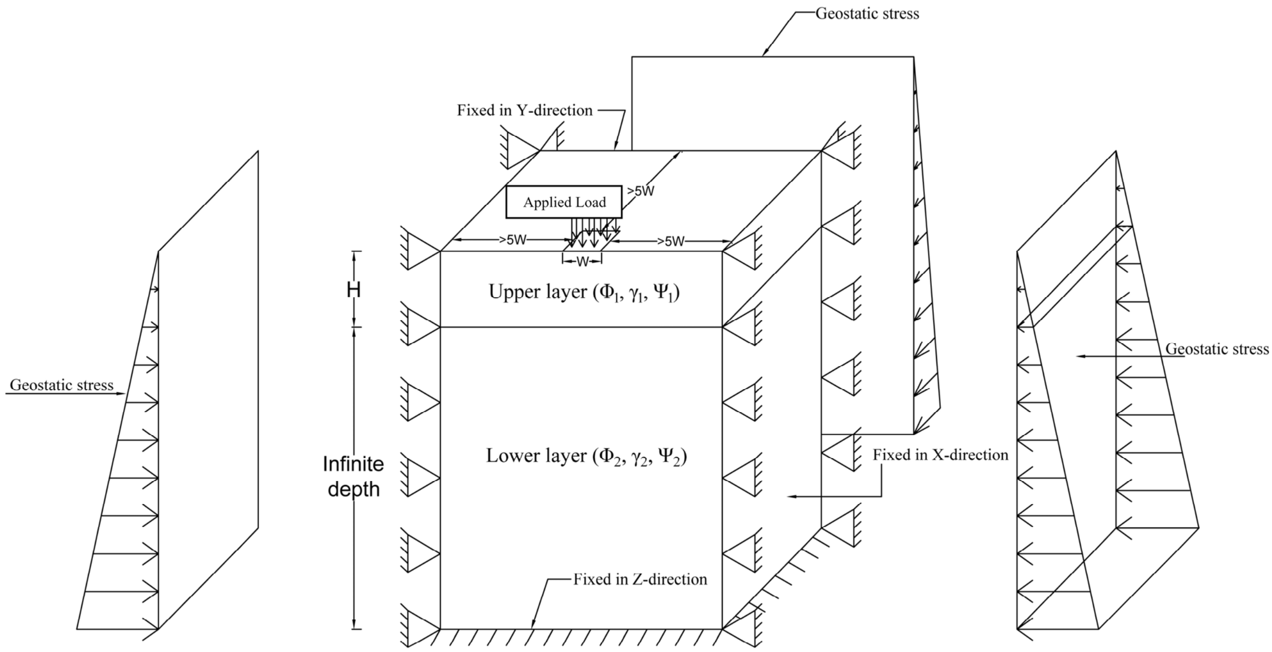

Fig. 1. Problem domain and boundary conditions

3. Finite element meshing and boundary conditions

A finite element technique was used to study the pressure settlement behaviour of the rectangular footing (L/W= 1.5) subjected to vertical loading and resting on layered sand using a commercially available software. Mohr Coulomb model was used in this study as it represents a 'first order' approximation of the sands behaviour by estimating a constant average stiffness resulting in faster computations to obtain a first estimate of deformations whereas the other soil hardening models takes more computational time as reported by Thakur and Dutta [32]. The soil element were considered to be elastic-plastic in nature. The element used in the modelling was C3D8R.

It is appropriate to mention here that, according to [12], footing was presumed to be a rigid that was only used as a means of transferring the load to the dense sand. Hence no actual footing was used in this modelling, but the load was directly applied to the rectangular surface (Fig. 1) of the upper layer of sand as per [12].

A two layered soil model was created having minimum dimensions >5W from footing edge in the X and Y direction and towards the bottom side. The necessary boundary conditions along all side of the model were taken into consideration to simulate the actual soil conditions. The finer meshing is used near the footing centre and coarser meshing is used as the distance increases from the edge of the footing as shown in Figure 2. Geostatic stress

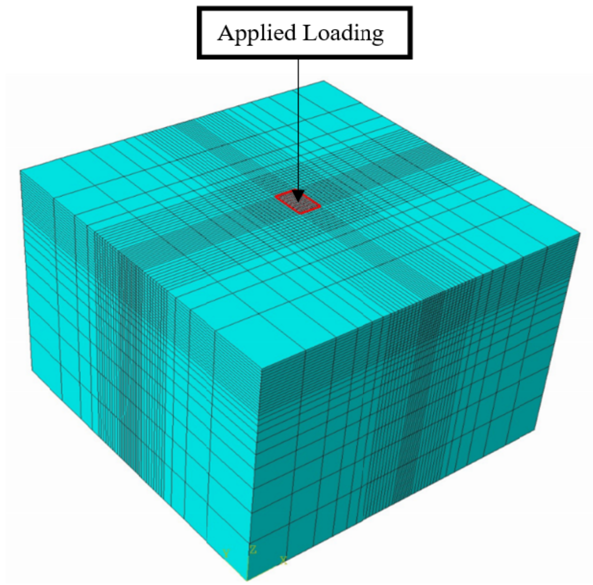

Fig. 2. Meshing of rectangular footing with L/W = 1.5 and resting on layered sand

was applied before the application of the vertical load at the centre of the rectangular footing. The convergence study conducted reveals that beyond 20150 elements, there is no significant improvement in the results. Further, increasing the number of elements to two times, results in an improvement of about 3-5% in the ultimate bearing capacity but the time required for the simulation becomes two fold. In addition, using further fine meshes, there will be more chances of accumulation error which may result in less useful results. Differential settlements were believed to be trivial because of the footing's rigidity. The touch nodes were therefore limited in such a way that the vertical displacement under a given load was similar. Figure 2 shows the 3D finite element mesh constructed for the rectangular footing on layered sand.

4. Software validation

Prior to carrying out the analysis, it was thought necessary to validate the selected finite element model and the software.

Hence, an additional analysis was performed for the strip footing resting on dense sand overlying loose sand and reported in literature by [3]. For this analysis, the upper dense and lower loose sand internal friction angles were taken as 47.7° and 34° respectively. The dry unit weights for the upper dense and lower loose sand layer were used as 16.33 kN/m^3 and 13.78 kN/m^3 respectively. Results of the present study after applying required boundary conditions to simulate the actual laboratory tests as per [3] were compared with the one reported by [27] and the comparison is shown in Table 1. Study of Table 1 reveals that the average deviation of the dimensionless ultimate bearing capacity was 6.11% at different thickness ratios (H/W). This deviation in the calculated bearing capacity could be attributed to reliability the empirical correlations used to derive the constitutive parameters of the soils.

Table 1.
Comparison of the results for the software validation

Dimensionless ultimate bearing capacity ($q_u/\gamma_1 W$)		
H/W	Hanna [3]	Present work
0.00	18.79	16.23
0.25	23.5	22.35
0.50	31.16	28.50
1.00	44.92	58.74
1.50	67	78.937
2.00	89.09	102.678

5. Results and discussions

Typical pressure settlement ratio plots obtained from the numerical analysis are shown in Figure 3. The ultimate bearing capacity (q_u) was taken as the minimum of peak pressure or pressure corresponding to normalised settlement (s/W) = 10%, whichever occurs earlier. If in the plot the peak was not clearly observed, a method of double tangent was used to calculate the pressure. After the validation of the software, the parametric study was performed for the selected H/W ratio as shown in Figure 4 and by varying φ_1 from 41° to 46° and φ_2 from 31° to 36°. The results of this analysis were presented in the following section.

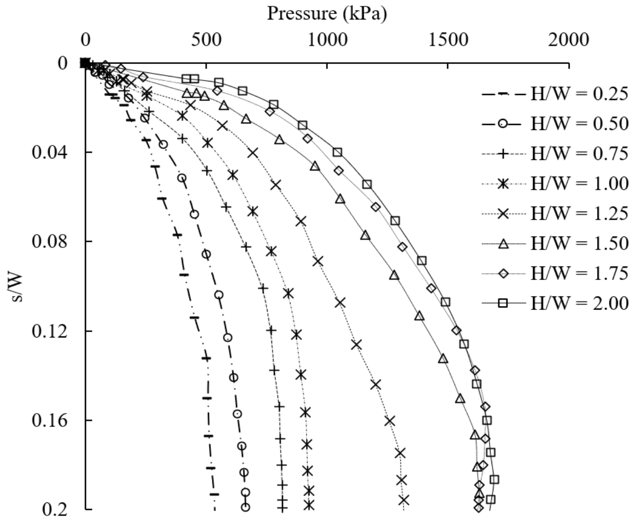

Fig. 3. Pressure settlement ratio plot for the rectangular footing on layered sand at φ_1 (41°) and φ_2 (31°) corresponding to different H/W ratio

5.1. Effect of H/W on dimensionless ultimate bearing capacity

For observing the effect of the thickness of the layered sand on the ultimate bearing capacity, it is required to have sufficient difference in their friction angle. So in the present study the upper layer denser sand layer friction angle was varied from 41° to 46° and for the lower layer of loose sand, it was varied from 31° to 36° for the parametric study. These range of friction angles were chosen as per [30].

Figure 4 shows the dimensionless ultimate bearing capacity obtained from the finite element analysis performed on a model rectangular footing subjected to vertical concentric load corresponding to different H/W

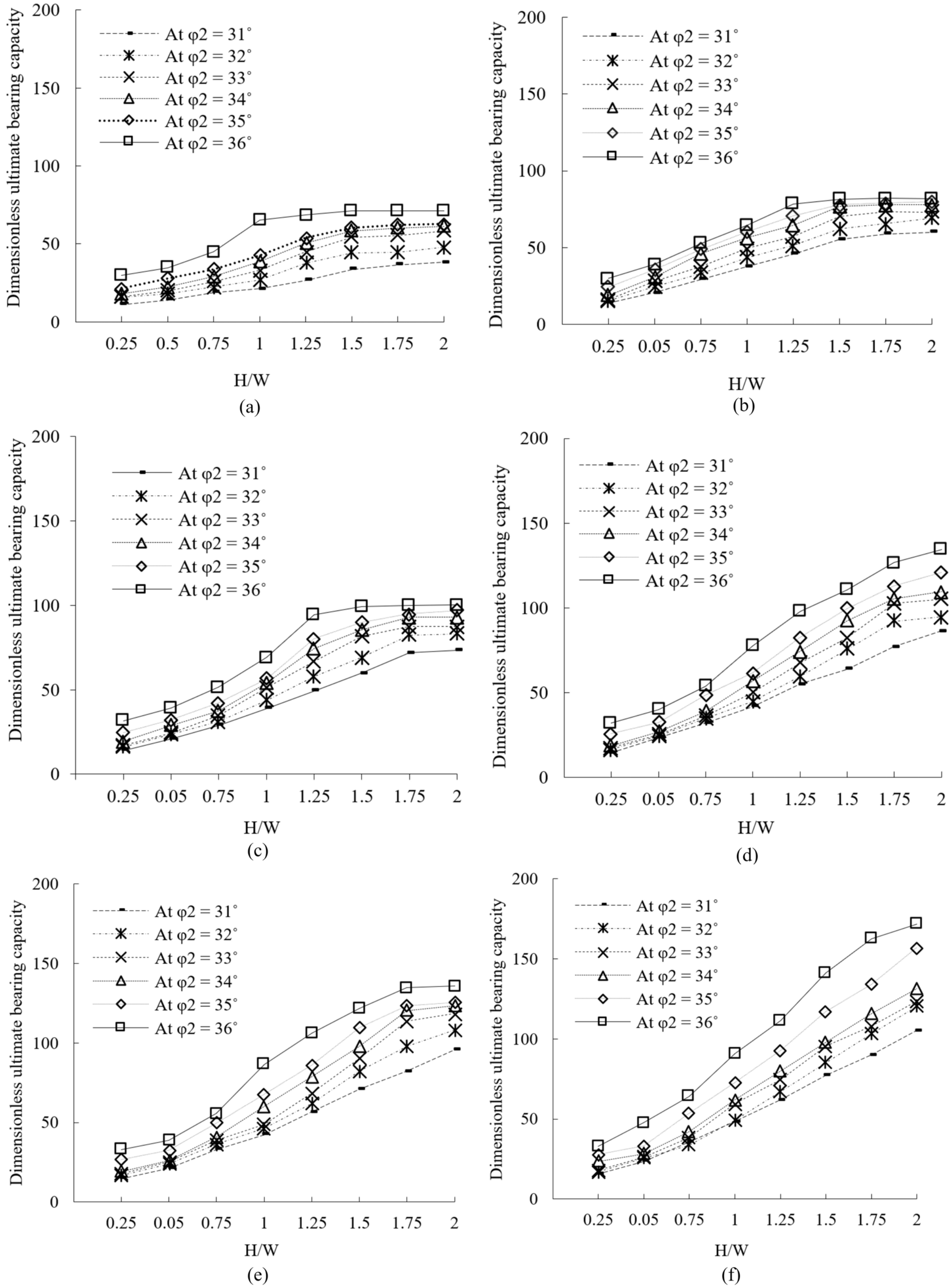

Fig. 4. Dimensionless ultimate bearing capacity versus H/W curves for upper dense sand layer friction angle (φ_1) (a) 41°, (b) 42°, (c) 43°, (d) 44°, (e) 45°, (f) 46°

ratios and resting on upper dense sand layer of restricted thickness overlying loose sand layer of limitless thickness. The H/W ratio was varied from 0.25 to 2 at an interval of 0.25. Study of Figure 4 reveals that the dimensionless ultimate bearing capacity increased with the increase in the friction angles of the upper dense as well as lower loose sand layer. This is attributed to the increase in the elastic modulus of sands with increase in the sand's friction angle. Further study of Figure 4 reveals that the dimensionless bearing capacity also increases with the increase in the H/W ratio. This is attributed to the fact that as H/W increases the thickness of the upper dense sand layer also increases which ultimately leads to increase in the dimensionless ultimate bearing capacity. For the upper dense and lower loose sand's friction angles of 46° and 36°, the observed dimensionless ultimate bearing capacity was the highest whereas it was lowest corresponding to friction angles of 41° and 31° for the upper dense and lower loose sands. The dimensionless ultimate bearing capacity was found to increase as evident from Figure 4 up to an H/W ratio of about 1.75 beyond which the increase was marginal. Similar findings were reported by [27] for the circular footing resting over upper dense sand overlying lower loose sand.

Comparison

The experimental results reported by [3] and the upper bound and lower bound results reported by [27] for the circular footing resting over dense sand overlying loose sand were compared with the results obtained in the present study. The present results of modelling for a rectangular footing with L/W=1were calculated in a dimensionless form and the same were compared with the results of [3] and [27] for the circular footing as both footings have similar shape factor. It is pertinent to mention here that [3] and [27] used the friction angle of the upper dense and lower loose sand layer as 47.7° and 34° respectively. Results of the present study after applying required boundary conditions to simulate the actual laboratory tests as per [3] were compared with the one reported by [27] and the comparison is shown in Table 2 The results of comparison corresponding to different H/W ratio are shown in Table 2. Up to H/W = 1, study of Table 2 reveals that the present results were higher in comparison to the results of [3] and were in agreement with the lower and upper bound solution provided by [27]. For H/W >1, the present results were higher in comparison to the one reported by [3] and [27]. Further, for L/W=1, study of Table 2 reveals that the average present results were 8.25% and 1.51% higher with respect to the results of [3] and [27] respectively. This disparity in the dimensionless ultimate bearing capacity obtained in the present study with respect to the one reported in the literature can be attributed to the difference in the shape of the footing used for modelling as well as to the definition used in the present study where the actual footing was replaced by a load applied directly to the rectangular surface of the upper dense sand.

Vectorial displacement

Figure 5 shows the vectorial displacement for the rectangular footing on upper dense sand overlying lower loose sand for different H/W ratios. 3D modelling was carried out in present study. But only one side of the footing is represented at a time. Moreover the vectorial displacement on the upper side of footing's centre shows 3D view. Analysis of this figure reveals that the vectorial displacement vector crosses the lower loose sand layer with the increase in the upper dense sand layer thickness in general up to a H/W=1.5 beyond which the vectorial displacement vector remains contained in the upper dense sand layer. This shows that the ultimate bearing capacity depends upon the properties of upper dense as well as lower loose sand layers up to H/W=1.5.

Table 2.
Comparison of present finite element analysis results with the one reported in literature

Dimensionless ultimate bearing capacity ($q_u/\gamma_1 W$)				
H/W	Hanna [3]	Khatri et al [27]		Present work
		Lower Bound	Upper Bound	
0.00	22.41	16.04	17.18	15.96
0.25	24.41	22.05	23.58	17.61
0.50	36.75	34.41	39.50	25.77
1.00	61.23	90.76	93.35	91.12
1.50	94.95	109.47	116.32	150.86
2.00	141.87	156.73	163.83	182.23

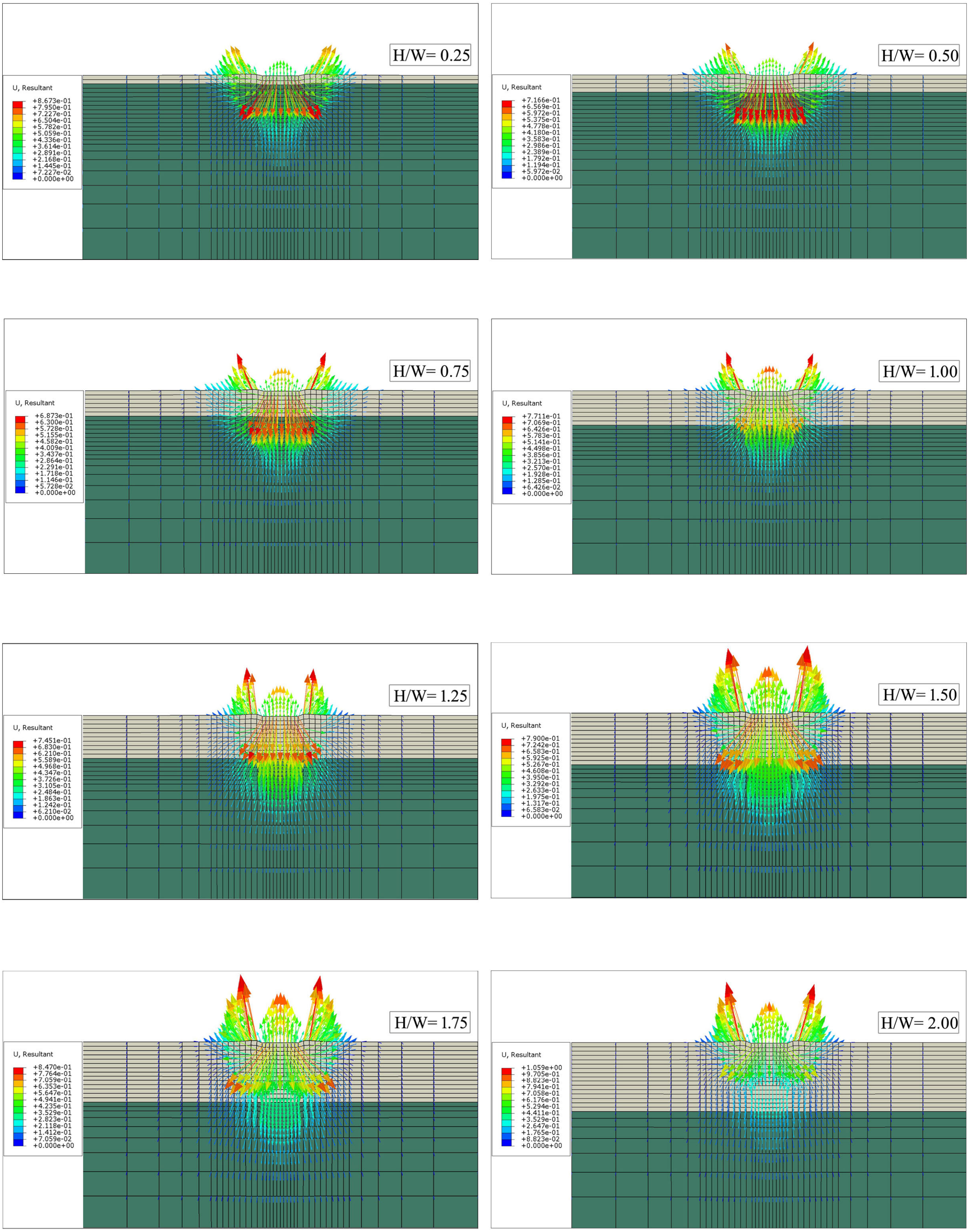

Fig. 5 Vectorial displacement of layered sand at different H/W ratio

5.2. Effect of L/W on dimensionless ultimate bearing capacity

Typical plots of the dimensionless ultimate bearing capacity obtained from the finite element analysis carried out on a model with an upper dense sand layer of limited thickness overlying a loose sand layer of unlimited thickness with a rectangular footing and subjected to vertical concentric load corresponding to different L/W ratios of 0.5, 1, 1.5, 2, 4, 6, 8 and10 are shown in Figure 6. The above study is carried out only for the L/W at 1.5 being a shorter dimension useful for quick analysis corresponding to different H/W ratios. But the numerical analysis for different L/W ratio is presented in Figure 6. This study was carried out for H/W ratio of 0.5 and 2 in order to study the effect of different L/W ratio on the dimensionless ultimate bearing capacity for the rectangular footing on layered sand. This analysis was carried out corresponding to the upper dense and lower loose sand layer's friction angles of 41° and 46° and 31° and 36° respectively.

Study of Figure 6 indicated that increasing the friction angles of the upper dense as well as the lower loose sand layer, the dimensionless ultimate bearing capacity increased. This is attributed to the increase in the elastic modulus of both the sands with an increase in the friction angle. For H/W = 0.5 and 2, study of Figure 6 shows that, the dimensionless bearing capacity decreases with the increase in the L/W ratio from 0.5 to 6 beyond which the dimensionless ultimate bearing capacity remains constant for all parameters combinations. This is attributed to the fact that under the constant load, the area of the rectangular footing increases with the increase in the L/W ratio resulting decrease in the dimensionless ultimate bearing capacity. The calculated dimensionless ultimate bearing capacity was the maximum for the upper dense and lower loose sand friction angles of 46° and 36°, while it was the lowest for the upper dense and lower loose sands corresponding to the friction angle of 41° and 31°. Similar observations were reported by [23] for the rectangular footing on different layered profile (dense sand overlying soft clay) with the increase in the L/W ratio.

Vectorial displacement

The vectorial displacement for the rectangular footing resting on upper dense sand placed on the lower loose sand layer corresponding to different L/W ratios for H/W ratio of 0.5 and 2 are shown in Figure 7 and Figure 8 respectively.

This study was carried out for two values of φ_1 (41° and 46°) and φ_2 (31° and 36°) in order to study the effect of different L/W ratio on the vectorial displacement for the rectangular footing on layered sand. Analysis of these figures show that the vectorial displacement vector shows a clear punching failure when the upper dense sand layer was having a very small thickness (H/W=0.5) as vectorial displacement vector reaching to the lower loose sand layer. Further, for H/W = 2, with the increase in the thickness of the upper dense sand layer, the vectorial displacement vector remains contained in the upper dense sand layer. Thus from the above it can be concluded that the dimensionless ultimate bearing capacity of the rectangular footing depends upon the properties of both the upper dense and lower loose sand layers.

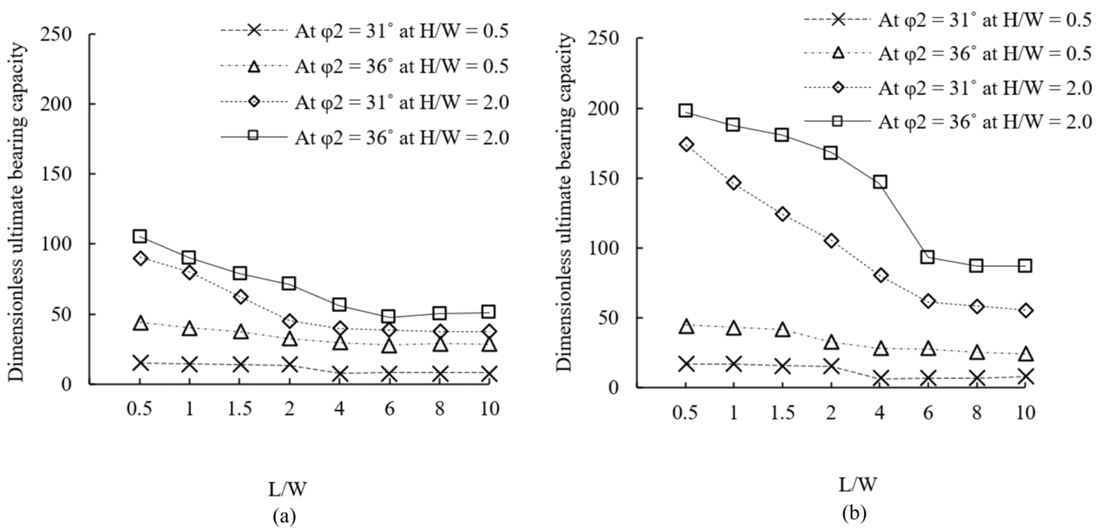

Fig. 6. Dimensionless ultimate bearing capacity versus L/W curves for upper dense sand layer friction angle (φ_1) (a) 41°, (b) 46°

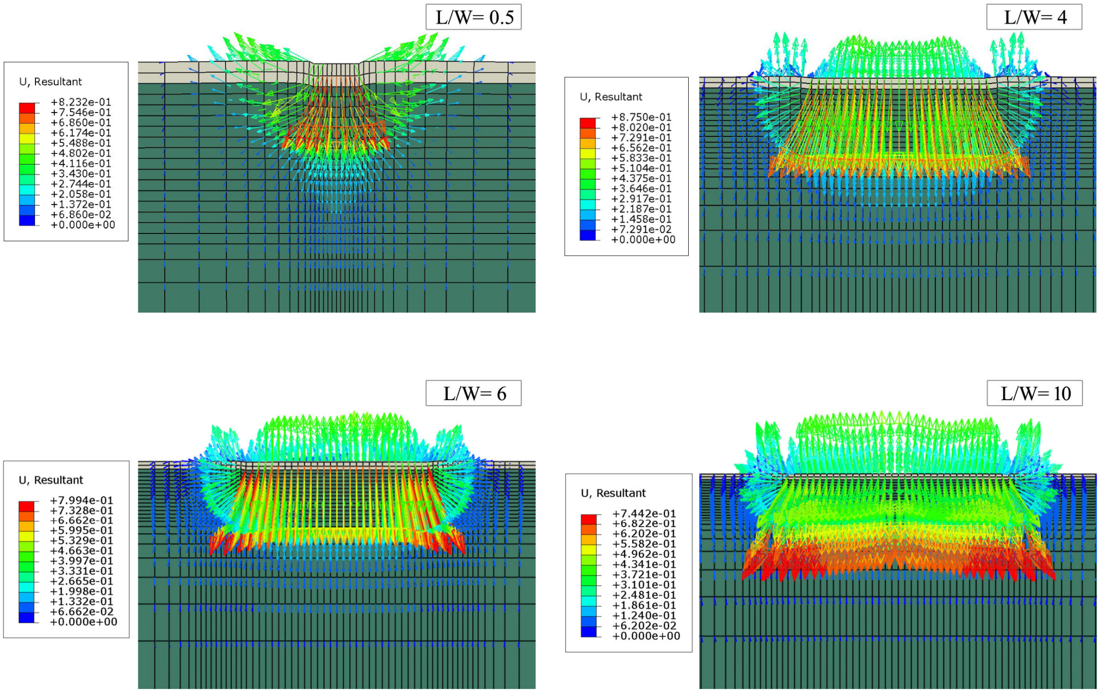

Fig. 7. Vectorial displacement of rectangular footing on layered sand for φ_1 (41°) and φ_2 (31°) at different L/W ratio for H/W ratio of 0.5

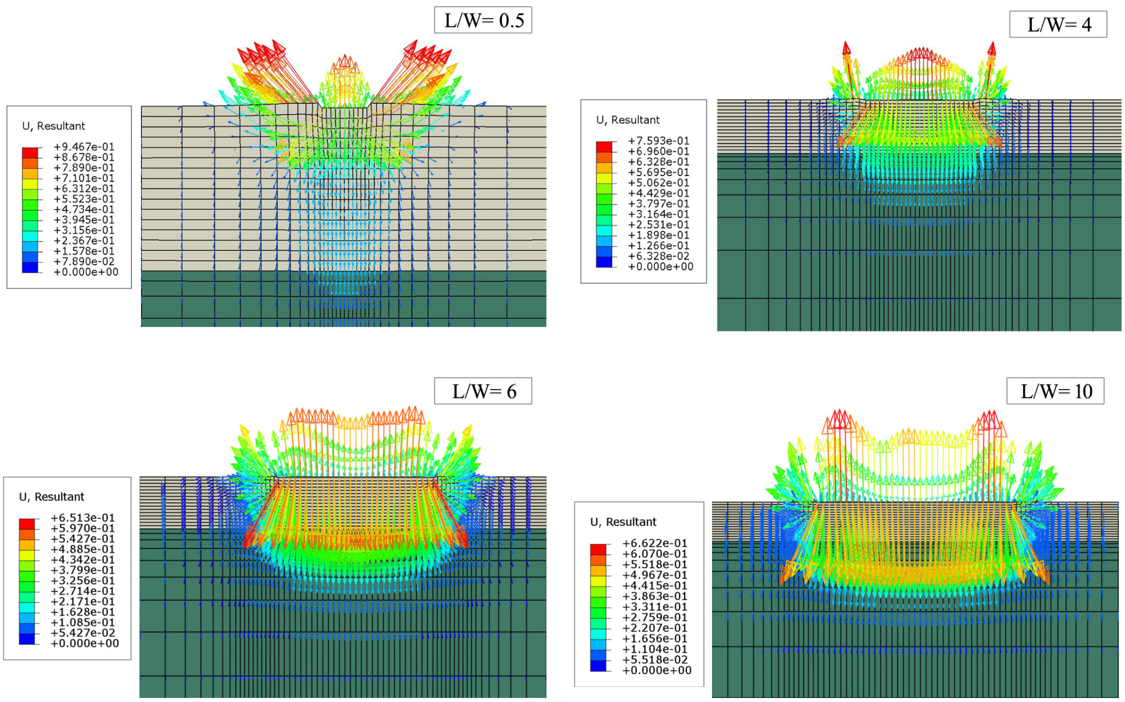

Fig. 8. Vectorial displacement of rectangular footing on layered sand for φ_1 (41°) and φ_2 (31°) at different L/W ratio for H/W ratio of 2

6. Conclusions

Using the finite element analysis, the dimensionless ultimate bearing capacity of the rectangular footing resting on upper dense sand layer overlying lower loose sand layer was numerically calculated. The numerical findings were presented in terms of a dimensionless ultimate bearing capacity in order to estimate the improvement in the bearing capacity for (1) different thicknesses of the upper sand layer and (2) different combinations of the friction angles of upper dense and lower loose sand layers. Based on the results presented in this paper and the discussions made, the following conclusions are put forward.

1. The dimensionless ultimate bearing capacity was found to increase up to an H/W ratio of about 1.75 beyond which the increase was marginal.
2. Up to H/W = 1, the present results were higher in comparison to the results of Hanna's and were in agreement with the lower and upper bound solution reported in literature.
3. For H/W>1, the present results were higher in comparison to the one reported in literature.
4. For L/W=1, the average dimensionless ultimate bearing capacity obtained the present study were 8.25% and 1.51% higher with respect to the results reported in literature.
5. The vectorial displacement vector crosses the lower loose sand layer with the increase in the upper dense sand layer thickness in general up to a H/W=1.5 beyond which the vectorial displacement vector remains contained in the upper dense sand layer.
6. For H/W = 0.5 and 2, the dimensionless bearing capacity decreases with the increase in the L/W ratio from 0.5 to 6 beyond which the dimensionless ultimate bearing capacity remains constant for all combinations of parameters.
7. The dimensionless ultimate bearing capacity was the maximum for the upper dense and lower loose sand friction angles of 46° and 36°, while it was the lowest for the upper dense and lower loose sands corresponding to the friction angle of 41° and 31°.
8. For H/W=0.5, the vectorial displacement vector shows a clear punching failure when the upper dense sand layer was having a very small thickness as vectorial displacement vector reaching to the lower loose sand layer.
9. For H/W = 2, with the increase in the thickness of the upper dense sand layer, the vectorial displacement vector remains contained in the upper dense sand layer.

Notations

Notations used in the article:
L – length of rectangular footing,
W – width of rectangular footing,
H – thickness of the upper dense sand layer,
γ – unit weight of sand,
φ – internal soil friction angle of sand,
μ – poisons ratio,
E – modulus of elasticity,
Ψ – dilation angle,
L/W – length to width ratio,
H/W – thickness ratio,
q_u – ultimate bearing capacity,
$q_u/\gamma_1 W$ – dimensionless ultimate bearing capacity,
s/W – normalized settlement.

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Conflict of interest

The authors have no conflict of interest with anyone related to the material presented in the paper.

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