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Uplift capacity of strip plate anchors in unsaturated sand

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ABSTRACT: In past, studies to investigate the uplift capacity of plate anchors embedded in saturated or dry sand have been conducted extensively. However, till date no study has ever been done on anchors in unsaturated sand. For a soil in unsaturated state, matric suction plays an important role in determining its shear strength and this affects the uplift capacity of anchors. Hence, the present study becomes relevant. In the present work, numerical solutions based on finite element limit analysis have been generated to find the uplift capacity of strip plate anchors under a fully bonded condition over a range of values of width of anchor, angle of internal friction, embedment depth and location of water table. The effect of different flow conditions and other parameters like van Genuchten SWRC model parameters, saturated unit weight was also seen. Modified Mohr-Coulomb yield criterion is used to incorporate the contribution of suction stress to the failure condition. For a few typical cases, failure patterns have also been generated. The solutions from the present study are compared with the available results in literature corresponding to saturated or dry case.

Keywords: Uplift capacity; unsaturated soil; finite-element analysis; suction.

1 INTRODUCTION

Anchors are used to resist pullout forces acting on various structures like retaining walls and transmission towers. Various studies have been done in past to find the uplift capacity of plate anchors in dry or saturated sand. Rowe and Davis (1982) did a theoretical study on the behavior of plate anchors in sand. These results were compared with the model tests and other experimental data. The effect of anchor orientation, embedment, angle of friction, dilatancy, initial stress state and anchor roughness on the uplift capacity was seen. Laboratory and experimental studies on single and multi-plate anchors in sand include those done by Das and Yang (1987), Dickin (1988), Dickin and Laman (2007), Geddes and Murray (1996), Gizem Misir (2018), Kumar and Bhoi (2009), Liu et al. (2012), Rokonuzzaman and Sakai (2012), Tilak and Samadhiya (2021). Limit analyses to investigate the uplift capacity of a group of anchor plates in sand include Bhattacharya and Kumar (2016), Hicham Mokhbi et al. (2018), Kouzer and Kumar (2009), Kumar and Kouzer (2008), Merifield and Sloan (2006). All these studies are applicable for saturated or dry sand. But in reality, all the soil lying above the water table is mostly unsaturated and the analysis done on dry or saturated soil may lead to an over estimation of collapse load and may result in an over conservative design. In unsaturated sand the behavior is appreciably affected by the matric suction which in turn is dependent on the mechanical and hydraulic behavior of soil. It is also affected by the flow condition i.e., evaporation, no-flow or infiltration. The present study analyzes the uplift capacity of horizontal strip anchors in sand using lower bound finite element limit analysis. The conventional Mohr-Coulomb yield criterion is modified using the unified effective stress approach to include the contribution of suction stress to the ultimate failure state. The effect of width of anchor plate, embedment depth, angle of internal friction, water table position, flow condition on the uplift capacity was seen. The effect of other parameters like air entry pressure and pore size distribution parameters has also been examined and were found to be insignificant.

2 PROBLEM STATEMENT

The analysis is done on an anchor plate of width b embedded at a depth of d from the ground surface as shown in Figure 1(a). For the plane strain case to be applicable the thickness of the plate is considered negligible compared to its thickness. The water table is considered at a depth of h_w from the ground surface. The saturated unit weight, bulk unit weight and effective angle of internal friction of soil are γ_{sat}, γ and ϕ' respectively.

Half of the problem domain was considered and discretized into a number of triangular elements as shown in Figure 1(b). Figure 1(b) shows a typical coarser mesh, however, for the present analyses much finer meshes were used. The size of the domain was chosen such that the plastic yield points were contained inside the boundary and the collapse load does not change much when the size of the domain is further increased. The flow rate and the saturated hydraulic conductivity of soil is given by q_s and k_s, respectively. q_s

is taken positive for evaporation, zero for no-flow and negative for infiltration. The uplift capacity q_u is given as

$$q_u = \frac{P_u}{b} \quad (1)$$

where, P_u is the failure load.

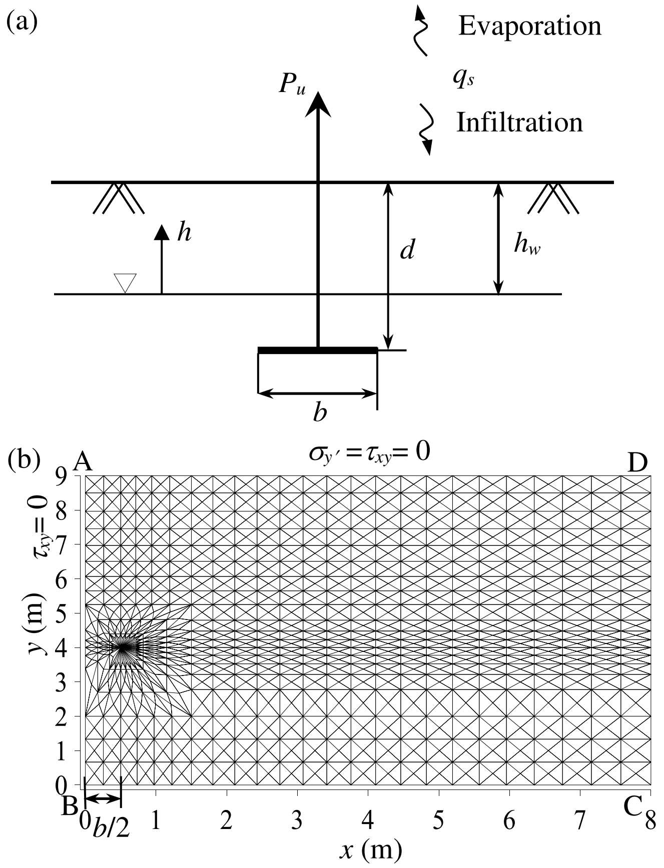

Figure 1. (a) Problem definition, and (b) a typical finite element mesh for d = 5 m and h_w = 7 m along with associated stress boundary conditions

3 METHODOLOGY

The present study was performed using a lower bound finite element limit analysis. The basic formulation was adapted from Sloan (1988) and the second order cone optimization technique by Makrodimopoulos and Martin (2006) was used. The stresses are assumed to obey the element equilibrium conditions, discontinuity equilibrium, boundary conditions and yield criterion in the whole domain.

The bulk unit weight (γ) in the unsaturated zone is not constant and is given by

$$\gamma = \left(\frac{G_s + eS}{1+e}\right)\gamma_w \quad (2)$$

where, G_s is the specific gravity of soil solids, e is the void ratio and S is the degree of saturation given by Lu and Godt (2013).

The boundary conditions are shown in Figure 1(b). The soil mass throughout the domain is assumed to follow the modified Mohr-Coulomb yield criterion given as

$$(\sigma'_x - \sigma'_y)^2 + (2\tau_{xy})^2 - \left(2c' \cos\phi' - \left(\sigma'_x + \sigma'_y + 2(u_a + \sigma^s)\right)\sin\phi'\right)^2 \leq 0 \quad (3)$$

where σ'_x and σ'_y are the effective normal stresses in the x and y direction, respectively in the cartesian coordinate system, τ_{xy} refers to shear stress in the x-y plane, u_a is the pore air pressure, and σ^s is the suction stress. σ^s can be expressed using Lu et al. (2010).

The non-linear constraints generated by the yield function is represented in a standard form of second order constraints by introducing auxiliary variables at each node (Makrodimopoulos and Martin, 2006).

After the global matrices and vectors are finalized, the second order conic optimization problem can be framed as:

$$\text{Objective function: Maximize } \{c\}^T\{\sigma\} \quad (4)$$

$$\text{Constraints: } [A]\{\sigma\} = \{B\} \quad (5)$$

where, $\{c\}$ = global vector of the coefficients of objective function

$[A]$ and $[B]$ are the global coefficient matrix and global vector of constants, respectively resulting from all the constraints from element equilibrium condition, stress boundary condition, discontinuity equilibrium and yield condition. The computer code was written in MATLAB (The Math Works, 2021) and the conic optimization was done using an optimization toolbox MOSEK ApS. (2015), available for MATLAB (The Math Works, 2021).

4 RESULTS AND DISCUSSION

A finite element lower bound analysis was carried out to examine the effect of various parameters on the uplift capacity of horizontal anchors placed in unsaturated sand. The investigation was carried out for a range of parameters, as given in Table 1. Irrespective of soil types, Lu and Likos (2004) suggested that the magnitude of rate of flow under different flux conditions i.e., evaporation, no flow and infiltration can be taken equal to 1.15×10^{-8} m/sec, 0 m/sec and -3.14×10^{-8} m/sec, respectively. The same flow values have been adapted in the present study.

Table 1. Range of various parameters used

Parameter	Range
d	1 m - 5 m
ϕ'	30°, 40°
γ_{sat}	17 kN/m^3 (when ϕ'= 30°) 20 kN/m^3 (when ϕ'= 40°)
b	1 m, 5 m
h_w	Depending on the value d
S_r	5%
α	0.1 kPa^{-1} - 0.5 kPa^{-1}
n	4 - 8

4.1 Variation of suction stress and unit weight of soil

Figures 2(a) and (b) show the variation of suction stress (σ^s) and unit weight (γ) of soil with height above the water table (h).

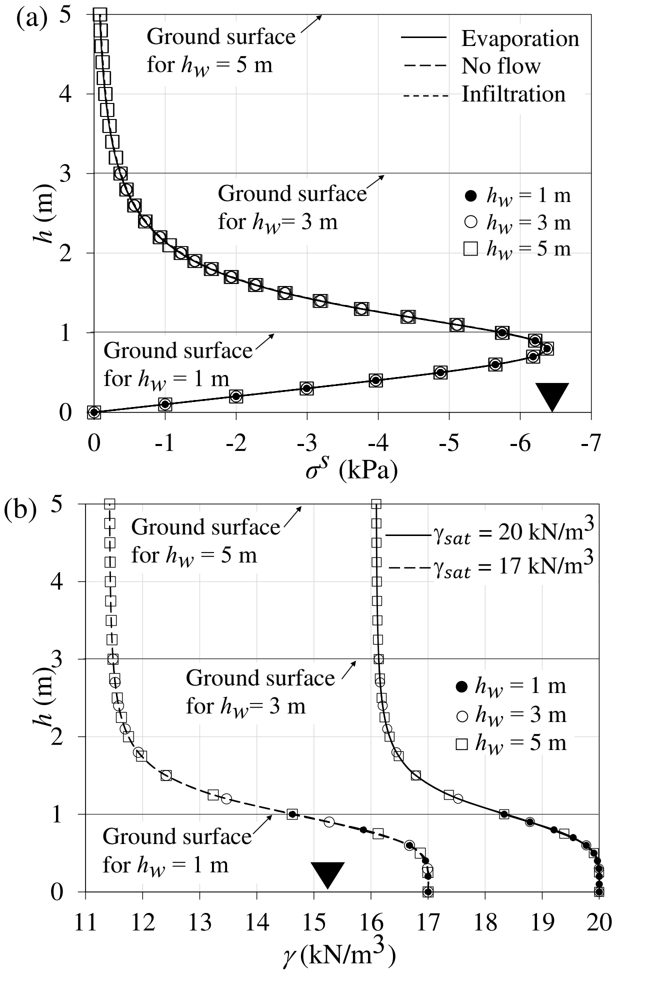

Figure 2. For d = 3 m and position of water table h_w = 1 m, 3 m and 5 m, (a) suction stress profile with depth: variation of σ_s (kPa) with h (m) for different flow conditions; (b) unit weight profile with depth: variation of γ (kN/m^3) with h (m) for γ_{sat} = 20 kN/m^3 and γ_{sat} = 17 kN/m^3

Figures 2(a) and (b) are plotted for d = 3 m with h_w = 1 m, 3 m and 5 m. In these graphs, when (i) h_w = 1 m, the water table lies above the anchor plate, where h = 0 and 1 m represent position of water table and ground surface, respectively, (ii) h_w = 3 m, the water table is located at the anchor level where h = 0 and 3 m represent position of water table and ground surface, respectively, (iii) h_w = 5 m, the water table is located below the anchor level where h = 0 and 5 m account for position of water table and ground surface, respectively.

In Figure 2(a) the flow rate was taken as 1.15×10^{-8} m/sec, 0 m/sec and m/sec -3.14×10^{-8} for evaporation, no-flow and infiltration, respectively. The variation of suction stress (σ^s) with depth can be seen from Figure 2(a). It can be seen that the flow condition does not have much effect on the magnitude of σ^s i.e., the difference in the value of σ^s in case of evaporation, no-flow and infiltration is negligible for sand. The reason can be attributed to the grain size of the sand and the seepage conditions. Mathematically, it can be explained by looking into the term q/k_s in the expression of suction stress given by Lu et al. (2010). As the saturated hydraulic conductivity (k_s) is greater in the coarse-grained soils, the value of q/k_s is lower, having a smaller effect on the suction stress. However, the suction stress increases with an increase in vertical distance from the water table and attains a maximum value at the ground surface. Figure 2(b) shows the variation of γ in the unsaturated soil with height above the water table for a hydrostatic case. The variation has been shown for two values of γ_{sat} i.e.,17 kN/m^3 for and 20 kN/m^3. The value of γ is maximum at the water table level and reaches a minimum value at the ground surface.

4.2 Effect of van Genuchten parameters

Figure 3 shows the variation of uplift capacity, q_u with the van Genuchten SWRC parameters, α and n. The variation has been plotted for a d = 3 m and h_w = 5 m. In further results the variation of q_u with h_w for different values of d, ϕ' and γ_{sat} have been produced by taking α = 0.1 and n = 5.

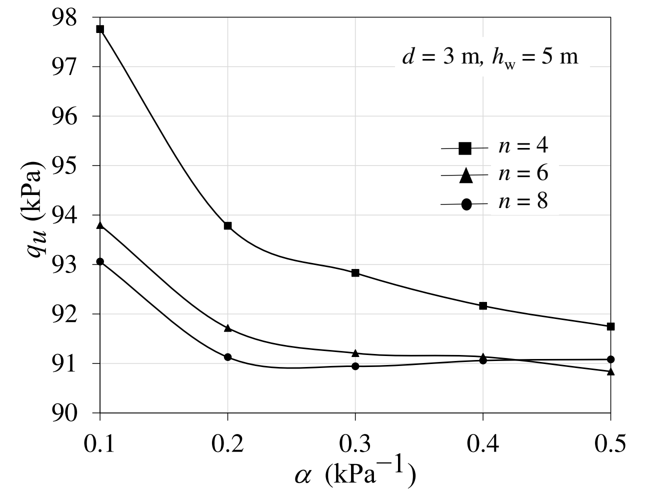

Figure 3. Variation of q_u (kPa) with α (kPa^{-1}) and n for ϕ' = 30°, d = 3 m, h_w = 5 m and γ_{sat}= 17 kN/m^3

4.3 Effect of position of water table

Figures 4(a-d) show the notable effect of position of water table on the anchor capacity q_u under different flow conditions. The study has been done for three positions of water table. (i) when water table is at the ground surface, $h_w = 0$, (ii) when the water table is at the anchor level, $h_w = d$, and (iii) when the water table lies below the level of anchor plate, $h_w > d$. Therefore, for d = 1 m, the analysis has been done for the position of water table $h_w = 0$, 1 m and 3 m. For $d = 3$ m, h_w is taken equal to 0, 3 m and 5 m. When $d = 5$ m, h_w is 0, 5 m and 7 m.

It was seen that for a particular embedment depth, an increase in the depth of the water table from the ground surface increased the uplift capacity at first but as the depth of water table further increases beyond a certain value, the uplift capacity then reduces. This may be due to the reason that the suction stress in sand first increases then decreases with an increase in the depth of the water table which significantly affects the anchor stability.

4.4 Effect of width of anchor

The present analysis was done for the width of anchor b = 1 m and 2 m. Figure 4(a) is plotted for $\phi' = 30°$, $\gamma_{sat} = 17$ kN/m^3, b = 1 m and Figure 4(b) is plotted for $\phi' = 30°$, $\gamma_{sat} = 17$ kN/m^3, b = 2 m. It can be seen that as the width of anchor increases the uplift capacity also increases. This is due to an increase in the contact area between the soil and anchor which increases the overall stability of the anchor plate. The same can be seen from the comparison of Figures 4(c) and (d) which are plotted for $\phi' = 40°$.

4.5 Effect of flow condition

Figures 4(a-d) show that flow conditions do not have any effect on the uplift capacity of anchor plate in sand. This is because the suction stress in sand does not change much with change in the flow condition as already discussed in section 4.1.

4.6 Effect of embedment depth and shear strength parameters of soil

The magnitude of the uplift capacity, q_u is found to increase as the embedment depth increases, since for increased depth more sand is above the anchor plate to resist the uplift. Also, the uplift capacity increases substantially with increase in the value of ϕ' which is evident from Figures 4(a-d). Greater the value of ϕ' more is the resistance of the soil to withstand the loads coming on it and greater is the uplift resistance.

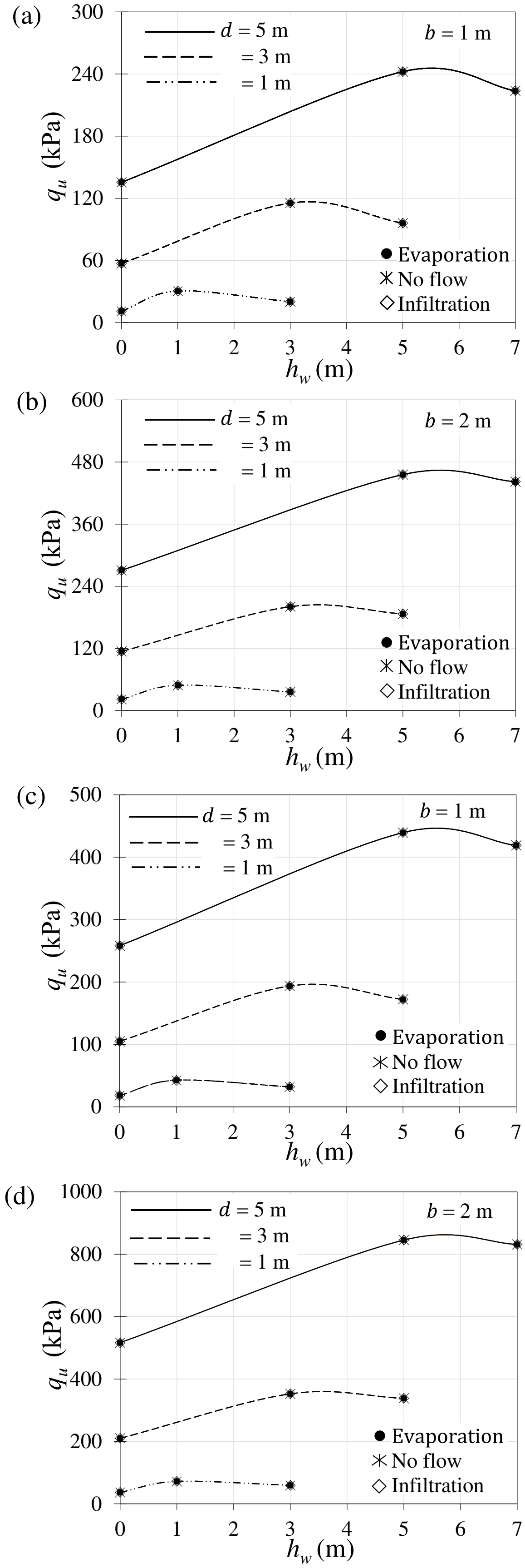

Figure 4. Variation of q_u (kPa) with h_w (m) under different flow conditions for different values of d with (a) $\phi' = 30°$, γ_{sat}= 17 kN/m^3, b = 1 m; (b) $\phi' = 30°$, γ_{sat}= 17 kN/m^3, b = 2 m; (c) $\phi' = 40°$, γ_{sat}= 20 kN/m^3, b = 1 m; (d) $\phi' = 40°$, γ_{sat}= 20 kN/m^3, b = 2 m

4.7 Failure patterns

The modified Mohr-Coulomb yield criterion given by Equation 3 can be expressed in the form of a *t/s* ratio, where, $t = (\sigma'_x - \sigma'_y)^2 + (2\tau_{xy})^2$; and $s = \left(2c' \cos\phi' - \left(\sigma'_x + \sigma'_y + 2(u_a + \sigma^s)\right)\sin\phi'\right)^2$. At ultimate shear failure *t/s* is equal to unity, and in a non-yielding state *t/s* is less than unity. Figures 5(a-c) under evaporation for $d/b = 3$ show that the zone of failure (the red part) is larger for the one with higher (i) h_w for the same values of ϕ', since an increase in the zone of unsaturation due to lowering of water table increases the suction stress and (ii) angle of internal friction for same values of h_w owing to increase in the shear strength of sand, which results in higher uplift capacity. These failure patterns validate the findings mentioned in the previous sections that the uplift capacity is (i) higher for higher depths of water table, (ii) higher for higher internal friction angle of soil.

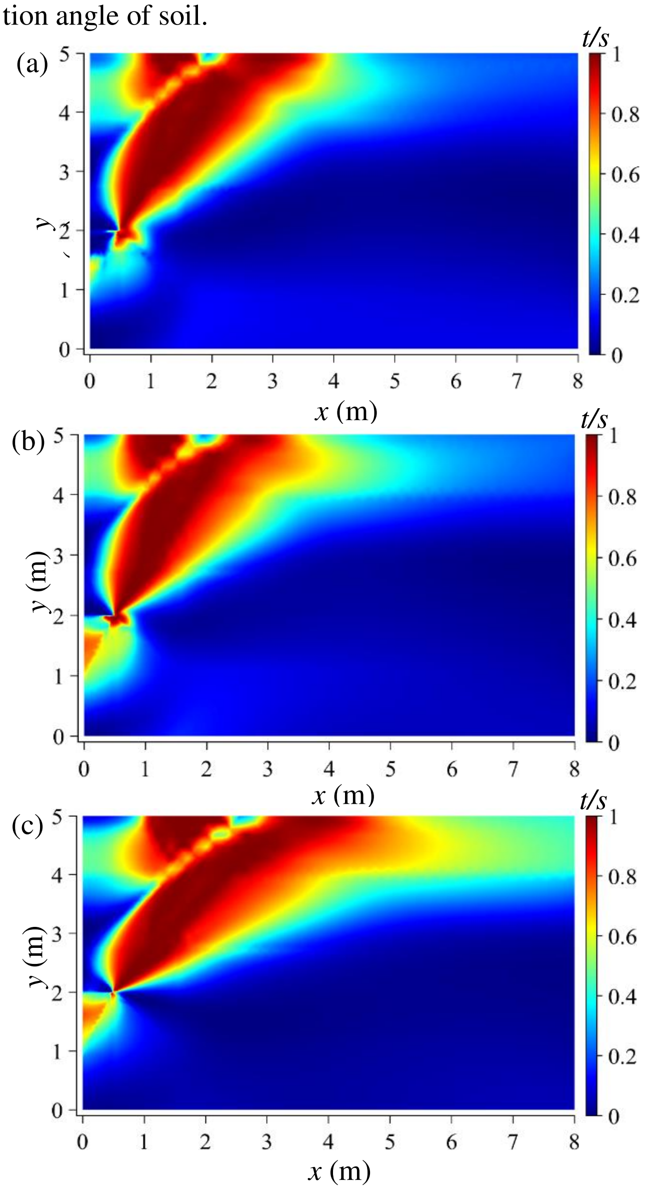

Figure 5. For d = 3 m, failure patterns under evaporation for (a) $\phi' = 30°$, $\gamma_{sat} = 17$ kN/m^3, $h_w = 0$; (b) $\phi' = 30°$, $\gamma_{sat} = 17$ kN/m^3, $h_w = 3$ m; and (c) $\phi' = 40°$, $\gamma_{sat} = 20$ kN/m^3; $h_w = 3$ m

5 VALIDATION

In past literature no solutions are available to find the uplift capacity of strip anchors embedded in unsaturated sand. Hence, the uplift capacity obtained from the present analysis for saturated case ($h_w = 0$ m) is compared with those applicable for anchors in saturated or dry sand from literature. The comparison of results is shown in Figure 6. Merifield and Sloan (2006) have done a numerical investigation and presented the lower bound solutions on the ultimate pull out loads of anchors. Kumar and Kouzer (2008) provided the results using upper bound finite element limit analysis and linear programming. The present results agree quite well with the results from the above two researches for saturated sand.

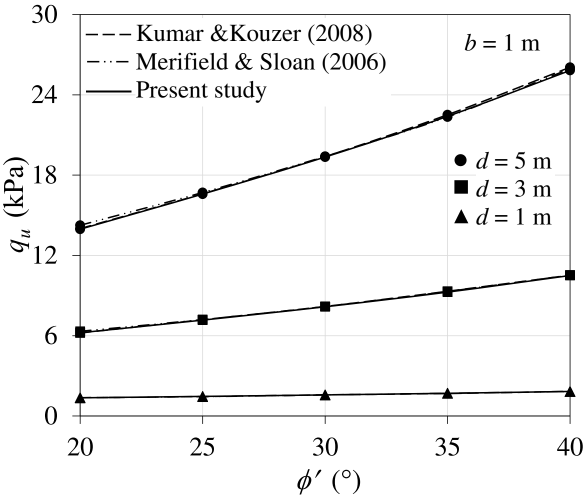

Figure 6. Comparison of variation of q_u with ϕ' for different embedment ratios obtained from the present study with results reported in literature for dry sand

6 CONCLUSIONS

The following major conclusions can be drawn from the present study

1. The anchor capacity is not affected much by the flow conditions. This is because the suction stress does not change much with change in flow conditions for sand. However, the anchor capacity increases with increase in the depth of the water table and width of anchor as can be seen from Figures 4(a-d). As water table lowers from the ground surface, the zone of unsaturation increases leading to increased suction stress. And as the anchor width increases, the contact between the anchor and the sand increases, thus the resistance to uplift is enhanced.
2. From Figures 4(a-d), the uplift capacity enhances with increase in the angle of internal friction owing to increase in the shear strength of sand. Also, the uplift capacity increases with increase in the embedment ratio of anchor because as the embedment depth increases, the overburden pressure owing to the weight of sand increases the uplift resistance.

3. The yielding zone i.e., the mass of soil involved in offering resistance to anchor at ultimate failure is higher for higher values of h_w and ϕ' as can be seen from Figures 5(a-c).

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