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Uplift Capacity of Horizontal Strip Anchors in Layered Sands

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Introduction

The calculation of forces exerted by the soil against structures was one of the earliest problems in soil mechanics. Active earth pressure, passive earth pressure and earth pressure at rest are the three stages of stress in soils which are of main interest in the analysis and design of earth retaining structures. Determination of uplift capacity of anchors is considered as a passive earth pressure problem with negative delta case. Anchors are primarily designed and constructed to resist outwardly directed loads imposed on the foundation of a structure. These outwardly directed loads are transmitted to the soil by the anchors. Earth anchors of various types are now used for uplift resistance of transmission towers, utility poles, aircraft moorings, submerged pipelines and tunnels. Anchors are also used for tie back resistance of earth retaining structures, at bends in pressure pipelines etc. Horizontal plate anchors are used in the construction of foundation subjected to uplift load.

Various theories are available for the determination of passive earth pressure. The most widely accepted theories to estimate earth pressure are those of Coulomb (1776), Rankine (1857), Taylor (1937), Caquot and Kerisel (1948), Sokolovski (1960) and Rosenfarb and Chen (1972). Janbu (1957), Shields and Tolunay (1973), Kumar and Subba Rao (1997) and Nayak (2000) have obtained passive force using method of slices for homogeneous soil.

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Meyerhof and Adams (1968) and Nayak (2000) have developed an approach for the determination of uplift capacity of strip anchors in homogeneous soils (treating the problem as passive earth pressure problem). Bouazza and Finlay (1990), Bouazza (1996) and Manjunatha (1997) have published few results on uplift capacity of plate anchors in layered sands. However, little work is published in the area of uplift capacity of anchors in layered sands. Keeping in view the lack of information in the area of uplift capacity of plate anchors in layered soils, study in this area is carried out and presented in this paper.

The objective of this paper is to propose a simple method to obtain passive earth force in layered sands and to use the same for the determination of uplift capacity of strip anchors in layered sands. Uplift capacity factors obtained from the analysis will be of use for the practising engineers.

Passive Earth Force

Passive force for layered sands is determined considering logarithmic spiral failure surface. Analysis is carried out for $\delta/\phi = -2/3$, (keeping in view the application of these results to estimate uplift capacity of strip anchors in layered sands), where δ and ϕ are wall friction angle and angle of internal friction of the soil respectively. However, the same approach can be used for any value of δ in between $-\phi$ to $+\phi$. Variable inter slice friction angle δ_i for the ith slice is considered in the form,

$$\delta_i = \delta\left(x_i/x_o\right)^F \tag{1}$$

where δ = angle of wall friction (= $-2/3\phi$),

x_i = horizontal distance from ith slice to the point where failure surface meets the ground,

x_o = horizontal extent of failure surface from the wall,

F = interslice friction factor.

Failure Surface

The analysis is based on the assumption that the failure surface is a logarithmic spiral. Fig.1 shows the typical failure surface along with the geometrical details for layered sands. AB is the retaining wall and AEF is the discontinuous failure surface. AE is the failure surface for the bottom layer with centre at O_1 and EF is the failure surface for the top layer with centre at O_2. ϕ_t, D_t and γ_t are the frictional angle, thickness and unit weight of top layer sand respectively. The corresponding parameters for the bottom layer are denoted by ϕ_b, D_b and γ_b respectively. r_{ft} and r_{bt} are the final and

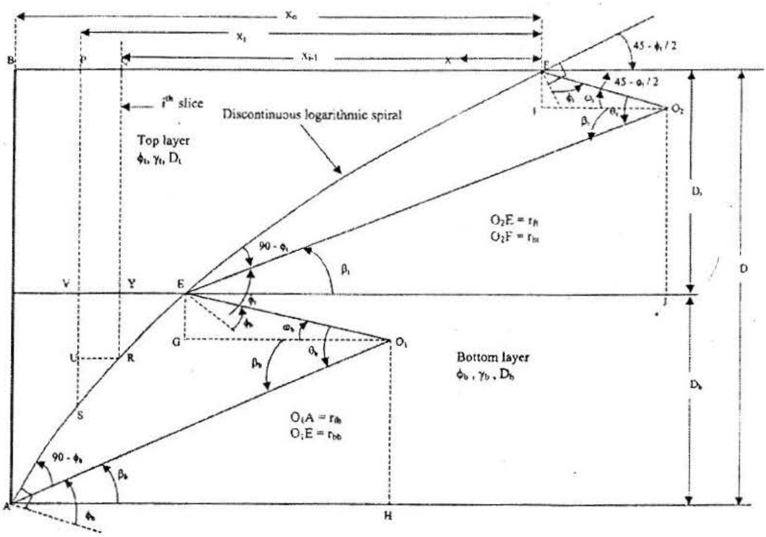

FIGURE 1 : Typical Failure Surface (Logarithmic Spiral) for Two-Layered Sand with Geometrical Details

initial radii of the logarithmic spiral in the top layer, where as r_{fb} and r_{bb} are the corresponding parameters for the bottom layer. β_t and β_b are the angle made by final radial line with the horizontal at the base in top and bottom layers respectively. The angles between the initial and final radii of the logarithmic spirals in top and bottom layers are denoted by θ_t and θ_b respectively. ω_t and ω_b are the angle made by the initial radial line of logarithmic spiral failure surface with horizontal in top and bottom layers respectively.

For the bottom layer (Fig.1),

$$r_{bb} \sin\omega_b + r_{fb} \sin\beta_b = D_b \tag{2}$$

where, $$r_{fb} = r_{bb}\, e^{\theta_b \tan\phi_b} \tag{3}$$

and $$\omega_b = \theta_b - \beta_b$$

For the top layer (Fig.1),

$$r_{bt} \sin\omega_t + r_{ft} \sin\beta_t = D_t \tag{4}$$

where $$r_{ft} = r_{bt}\, e^{\theta_t \tan\phi_t} \tag{5}$$

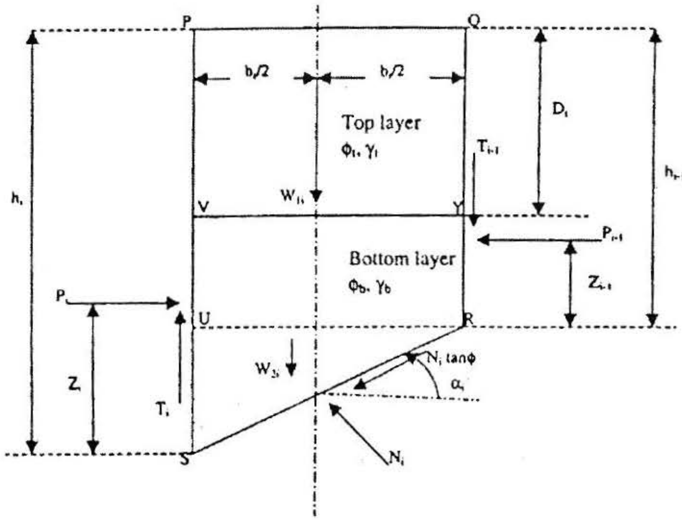

FIGURE 2 : Forces Acting on the Ith Slice

$$\theta_t = \beta_t + w_t \tag{6}$$

where $$w_t = 45 - \phi/2$$

Consider any slice PQRS as shown in Fig.1. Forces acting on the slice are shown in Fig.2. W_{1i} is sum of weight of the soil in the rectangular part PQYV (top layer part) and weight of soil in VYRU (lower layer part). W_{2i} is the weight of the soil mass in triangular region URS. α_i is the average angle made by the tangent to the logarithmic spiral with the horizontal at the base of the slice. h_i and h_{i-1} are the height of the i^{th} slice as shown in Fig.2. Z_i and Z_{i-1} are the vertical distance of point of application of passive force measured from the bottom as shown in Fig.2.

By considering the horizontal equilibrium of the slice,

$$N_i = \frac{(P_i - P_{i-1})}{(\tan\phi\cos\alpha_i + \sin\alpha_i)} \tag{7}$$

From the vertical equilibrium of the slice,

$$N_i = \frac{(W_i + T_{i-1} - T_i)}{(\cos\alpha_i - \tan\phi\sin\alpha_i)} \tag{8}$$

where

$$W_i = (W_{1i} + W_{2i})$$

$$W_{1i} = \left[\text{weight of top ayer portion} = \gamma_t D_t b_i\right] + \begin{bmatrix}\text{weight of rectangular portion of the bottom layer} \\ = \gamma_b \left(h_{i-1} - D_t\right) b_i\end{bmatrix}$$

$$W_{2i} = \begin{bmatrix}\text{weight of triangular portion of the bottom layer} \\ = \tfrac{1}{2}\, \gamma_b \left(h_i - h_{i-1}\right) b_l\end{bmatrix}$$

Equating Eqns.7 and 8, Passive force is given by,

$$P_i = \frac{\left[\left(W_i + T_{i-1}\right) f(\phi, \alpha) + P_{i-1}\right]}{\left(1 + f(\phi, \alpha)\tan\delta_i\right)} \tag{9}$$

where
$$f(\phi, \alpha) = \frac{\left(\sin\alpha_i + \tan\phi\cos\alpha_i\right)}{\left(\cos\alpha_i - \tan\phi\sin\alpha_i\right)} \tag{10}$$

and Tangential force is given by

$$T_i = P_i \tan\delta_i \tag{11}$$

where

$$\delta_i = \delta\left(x_i / x_o\right)^F \text{ and}$$

$$\delta = \frac{2}{3}\left(\frac{\phi_t D_t + \phi_b D_b}{D_t + D_b}\right)$$

By taking the moment of all the forces acting on the slice about its centre of the base,

$$Z_i = \frac{\begin{bmatrix} P_i\left\{\left(b_i/2\right)\tan\alpha_i\right\} - \left\{T_i + T_{i-1}\right\}\left(b_i/2\right) \\ \qquad + P_{i-1}\left\{Z_{i-1} + \left(b_i/2\right)\tan\alpha_i\right\} + W_{2i}\left(b_i/6\right)\end{bmatrix}}{P_i} \tag{12}$$

where

$$b_i = x_i - x_{i-1}$$

Finally, minimum passive earth force is obtained using the following steps.

1. Initial value of angle β_b is assumed.

2. A small initial value of r_{fb} (the length of final radial line of logarithmic spiral for the bottom layer) is assumed.

3. Assume a small value of θ_b, the angle between initial and final radial lines of logarithmic spiral for bottom layer.

4. For the above assumed values of β_b, r_{fb} and θ_b, the initial radius of logarithmic spiral for the bottom layer (r_{bb}) is calculated using the Eqn.3.

5. Check whether the logarithmic spiral exactly fits into the bottom layer using Eqn.2.

6. If not, increment θ_b at regular intervals and repeat step 4 and step 5.

7. Even after incrementing θ_b, if the logarithmic spiral does not fit as per Eqn.2, then increment r_{fb} and repeat from step 3. This step is carried out till Eqn.2 gets satisfied. Thus the failure surface for the bottom layer is fixed.

8. Once the logarithmic spiral for the bottom layer is fitted, the top layer failure surface is fixed based on the Eqns.4, 5 and 6 for an assumed value of β_t (assuming the exit angle at the ground surface as $45-\phi_t/2$ as shown in Fig.1).

9. Once the first trial failure surface is traced, the soil mass ABFEA (shown in Fig.1) is divided in to 'i' number of slices (i = 40).

10. The point of application of passive earth force on the back of the wall is assumed to be same as that obtained by the conventional method, which assumes top layer as surcharge over the bottom layer. Z_a denotes the vertical height of point of application of passive force from the bottom of the wall obtained by the conventional method. If $K_{p\gamma t}$ and $K_{p\gamma b}$ are the passive earth pressure coefficients obtained independently by the proposed method of slices for top and bottom layers respectively (single layer analysis assuming D_t = D and D_b = D respectively), then

$$Z_a = \frac{P_1\left(D_b + \frac{D_t}{3}\right) + P_2\left(\frac{D_b}{2}\right) + P_3\left(\frac{D_b}{3}\right)}{P_1 + P_2 + P_3} \tag{13}$$

where
$$P_1 = (1/2)K_{p\gamma t}\,\gamma_t\,D_t^2$$
$$P_2 = K_{p\gamma b}\,\gamma_t\,D_t\,D_b \quad \text{and}$$
$$P_3 = (1/2)K_{p\gamma b}\,\gamma_b\,D_b^2$$

Normal component of passive earth force by the conventional method is given by,

$$P_{pn} = P_1 + P_2 + P_3 \tag{14}$$

11. A small initial value of interslice friction factor F is assumed.

12. The interslice friction angle, δ_i for the i^{th} slice is calculated by Eqn.1.

13. Using Eqns.9, 11 and 12, values of P_i ,T_i and Z_i are calculated for all the slices.

14. For the last slice, check whether $Z_n = Z_a$. If not, change F and repeat from step 12 till $Z_n = Z_a$.

15. The normal component of passive earth force P_n on the back of the wall is thus established.

16. Various failure surfaces are considered by varying the values of β_t and the entire procedure (from step 8) is repeated.

17. More number of failure surfaces are considered by varying β_b and repeating the entire procedure from step 2.

18. The minimum value of P_n is selected (denoted by P_{pn}).

This analysis is carried out for D_t/D = 0.0, 0.25, 0.5, 0.75 and 1.0; ϕ_b = 25°, 30°, 35°, 40° and 45° and ϕ_t = 25°, 30°, 35°, 40° and 45°. The minimum values of normal component of passive force obtained for all the above cases are provided in Table 1. The corresponding passive earth pressure coefficients ($K_{p\gamma}$) are calculated and are reported in the same table.

Uplift Capacity of Horizontal Strip Anchors

Determination of the uplift capacity of anchors is considered as a passive earth pressure problem with negative delta case (in negative delta case under passive condition the wall moves up relative to the soil). Assumptions made in the analysis are,

TABLE 1 : Comparison of Passive Earth Force Obtained by Conventional Approach (Method I) and Proposed Theory (Method II)

ϕ_b	ϕ_t	D_t/D	Normal component of passive force, P_{pn} (kN)		Percentage Difference Between Method I and Method II	Passive Earth Pressure Coefficient $K_{p\gamma}$ ($= 2P_{pn}/\gamma D^2$)
			Method I	Method II		
25°	25°	0-1	987.00	987.00	0.00	1.41
	30°	0.25	1051.18	1011.64	3.76	1.40
		0.50	1102.75	1059.24	3.95	1.41
		0.75	1141.68	1102.93	3.39	1.42
	35°	0.25	1084.31	1029.69	5.04	1.40
		0.50	1164.75	1098.19	5.71	1.42
		0.75	1228.31	1173.62	4.45	1.44
	40°	0.25	1116.56	1026.02	8.11	1.37
		0.50	1223.25	1149.23	6.05	1.44
		0.75	1307.06	1247.73	4.54	1.47
	45°	0.25	1147.16	1056.97	7.86	1.39
		0.50	1275.13	1214.42	4.76	1.47
		0.75	1370.91	1312.39	4.27	1.48
30°	25°	0.25	1101.94	1065.26	3.33	1.37
		0.50	1049.75	999.60	4.78	1.33
		0.75	1011.44	963.90	4.70	1.33
	30°	0-1	1168.00	1168.00	0.00	1.46
	35°	0.25	1202.66	1155.80	3.90	1.42
		0.50	1231.25	1182.02	4.00	1.43
		0.75	1260.34	1191.50	5.46	1.42
	40°	0.25	1235.25	1172.95	5.04	1.42
		0.50	1291.00	1212.58	6.07	1.43
		0.75	1335.25	1252.07	6.23	1.43
	45°	0.25	1266.78	1197.23	5.49	1.43
		0.50	1344.13	1275.78	5.09	1.46
		0.75	1400.03	1310.34	6.41	1.44
35°	25°	0.25	1172.6	1131.90	3.47	1.39
		0.50	1090.50	1043.70	4.29	1.35
		0.75	1028.62	977.82	4.94	1.33
	30°	0.25	1240.19	1199.52	3.28	1.43
		0.50	1210.75	1161.30	4.08	1.41
		0.75	1186.69	1142.85	3.69	1.41

TABLE 1 : Continued

ϕ_b	ϕ_t	D_t/D	Normal component of passive force, P_{pn} (kN)		Percentage Difference Between Method I and Method II	Passive Earth Pressure Coefficient K_{pg} $(= 2P_{pn}/gD^2)$
			Method I	Method II		
	35°	0-1	1275.00	1275.00	0.00	1.50
	40°	0.25	1308.94	1252.88	4.28	1.45
		0.50	1335.75	1278.37	4.30	1.46
		0.75	1355.44	1307.04	3.57	1.47
	45°	0.25	1341.29	1269.67	5.34	1.45
		0.50	1389.88	1320.52	4.99	1.47
		0.75	1420.97	1345.95	5.28	1.46
40°	25°	0.25	1230.19	1190.70	3.21	1.40
		0.50	1120.75	1068.20	4.69	1.34
		0.75	1039.69	990.92	4.69	1.32
	30°	0.25	1298.50	1264.20	2.64	1.44
		0.50	1242.00	1205.4	2.95	1.42
		0.75	1198.50	1164.64	2.83	1.41
	35°	0.25	1333.69	1303.40	2.27	1.47
		0.50	1306.75	1256.14	3.87	1.44
		0.75	1287.19	1221.93	5.07	1.42
	40°	0-1	1368.00	1368.00	0.00	1.52
	45°	0.25	1400.66	1335.05	4.68	1.46
		0.50	1422.63	1352.13	4.96	1.46
		0.75	1433.91	1374.79	4.12	1.47
45°	25°	0.25	1264.97	1238.72	2.08	1.40
		0.50	1133.87	1087.80	4.06	1.32
		0.75	1041.22	998.59	4.09	1.31
	30°	0.25	1332.91	1298.50	2.58	1.42
		0.50	1254.63	1210.30	3.53	1.38
		0.75	1199.66	1157.61	3.51	1.38
	35°	0.25	1367.91	1337.70	2.21	1.45
		0.50	1319.13	1282.14	2.8	1.42
		0.75	1288.16	1243.39	3.48	1.42
	40°	0.25	1402.03	1372.00	2.14	1.46
		0.50	1380.13	1343.72	2.64	1.45
		0.75	1368.78	1325.99	3.13	1.45
	45°	0-1	1434.50	1434.50	0.00	1.51

1. When the anchor is pulled out, the failure surface is considered as a discontinuous logarithmic spiral.

2. Failure surface extends up to the ground surface (shallow anchor condition).

3. Strip anchor is rigid and does not yield.

4. Suction below the anchor plate is neglected.

5. Anchor rod contribution to uplift capacity of anchor is very small and hence it is neglected.

6. On an imaginary vertical wall face passing through the edge of anchor plate, wall friction δ is considered to be $(-2/3)\phi$, which is same as that considered by Meyerhof and Adams (1968) for anchors in single layer. For two layer soil system,

$$\phi = \frac{\phi_t D_t + \phi_b D_b}{D_t + D_b} \tag{15}$$

Uplift Capacity Factor, F_γ

Consider a horizontal strip anchor of width B at embedment depth D as shown in Fig.3a. The failure surfaces AE and A^1E^1 are considered as

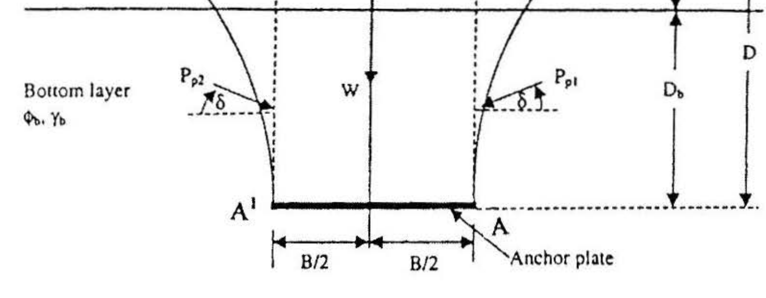

FIGURE 3a : Failure Surface for Horizontal Strip Anchor in Layered Sands

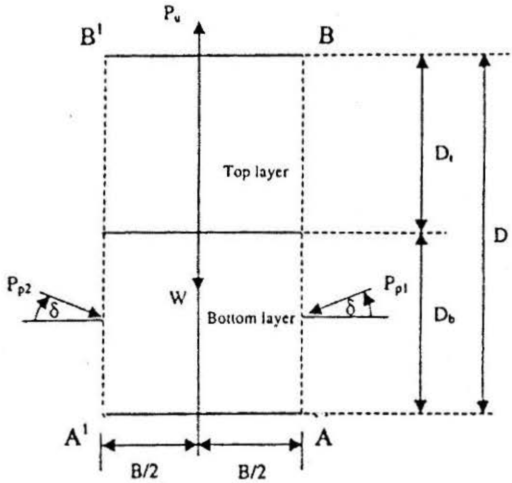

FIGURE 3b : Forces Acting on Central Soil Block ABA^1B^1

logarithmic spirals. The passive earth force P_{p1} on imaginary wall face AB is obtained by applying equilibrium conditions to soil mass ABE (Fig.3a). Similarly applying equilibrium conditions to soil mass $A^1B^1E^1$, the passive earth force P_{p2} on imaginary wall face A^1B^1 is obtained.

Considering the equilibrium of forces acting on the central soil block ABA^1B^1 (shown in Fig.3b) along the pull direction, the gross pullout load P_u is determined.

$$P_u = P_{p1} \sin\delta + P_{p2} \sin\delta + W \tag{16}$$

where W = weight of the soil mass ABB^1A^1

$$P_u = 2P_u \sin\delta + W \tag{17}$$

where $P_{p1} = P_{p2} = P_p$

Expressing P_p in the form,

$$P_p \cos\delta = (1/2) K_{p\gamma}\, \gamma D^2 \tag{18}$$

where $$\gamma = \frac{\gamma_t D_t + \gamma_b D_b}{D_t + D_b}$$

Substituting Eqn.18 in Eqn.17,

$$P_u = W + K_{p\gamma}\gamma D^2 \tan\delta \tag{19}$$

The net ultimate uplift capacity q_{unet} is expressed as,

$$q_{unet} = \frac{P_u - W}{B} \tag{20}$$

Substituting Eqn.19 in Eqn.20 and simplifying,

$$q_{unet} = K_{p\gamma}\gamma\left(D^2/B\right)\tan\delta \tag{21}$$

$$q_{unet} = K_{p\gamma}\gamma\left(D^2/B^2\right)B\tan\delta \tag{22}$$

$$q_{unet} = K_{p\gamma}\gamma\lambda^2 B\tan\delta \tag{23}$$

where $\lambda = D/B$ = embedment ratio

$$q_{unet} = \frac{1}{2}B\gamma\left(2K_{p\gamma}\lambda^2\tan\delta\right) \tag{24}$$

Expressing the ultimate anchor pullout capacity in sands as,

$$q_{unet} = \frac{1}{2}B\gamma F_\gamma \tag{25}$$

where, F_γ is the uplift capacity factor and is given by,

$$F_\gamma = 2K_{p\gamma}\lambda^2\tan\delta \tag{26}$$

Results and Discussion

Using Eqn.26, the uplift capacity factors are obtained for the following cases: D_t/D = 0.0, 0.25, 0.50, 0.75 and 1.0; ϕ_b = 25°, 30°, 35°, 40° and 45°; ϕ_t = 25°, 30°, 35°, 40° and 45° and λ = D/B = 2, 6, 10 and 15. The variation of uplift capacity factor F_γ for various cases are provided in Tables 2 to 6 for ϕ_b = 25°, 30°, 35°, 40° and 45° respectively. Meyerhof and Adams (1968) provided values of critical embedment ratio (λ_{cr}) beyond which

TABLE 2 : Uplift Capacity Factors F_γ for λ = 2, 6, 10 and 15 when $\phi_b = 25°$

ϕ_f	D_f/D	F_γ			
		$\lambda = 2$	$\lambda = 6$	$\lambda = 10$	$\lambda = 15$
25°	0 – 1.00	3.38	30.42	84.50	190.13
30°	0.25	3.53	31.77	88.25	198.56
	0.50	3.74	33.66	93.50	210.38
	0.75	3.95	35.55	98.75	222.19
35°	0.25	3.71	33.39	92.75	208.69
	0.50	4.13	37.17	103.25	232.31
	0.75	4.58	41.22	114.50	257.63
40°	0.25	3.81	34.29	95.25	214.31
	0.50	4.58	41.22	114.50	257.63
	0.75	5.28	47.52	132.00	297.00
45°	0.25	4.05	36.45	101.25	227.81
	0.50	5.07	45.63	126.75	285.19
	0.75	5.95	53.55	148.75	334.69

TABLE 3 : Uplift Capacity Factors F_γ for λ = 2, 6, 10 and 15 when $\phi_b = 30°$

ϕ_f	D_f/D	F_γ			
		$\lambda = 2$	$\lambda = 6$	$\lambda = 10$	$\lambda = 15$
25°	0.25	3.81	34.29	95.25	214.31
	0.50	3.53	31.77	88.25	198.56
	0.75	3.39	30.51	84.75	190.69
30°	0 – 1.00	4.25	38.25	106.25	239.06
35°	0.25	4.32	38.88	108.00	243.00
	0.50	4.54	40.86	113.50	255.38
	0.75	4.71	42.39	117.75	264.94
40°	0.25	4.51	40.59	112.75	253.69
	0.50	4.93	44.37	123.25	277.31
	0.75	5.33	47.97	133.25	299.81
45°	0.25	4.74	42.66	118.50	266.63
	0.50	5.45	49.05	136.25	306.56
	0.75	6.00	54.00	150.00	337.50

TABLE 4 : Uplift Capacity Factors F_γ for λ = 2, 6, 10 and 15 when ϕ_b = 35°

ϕ_t	D_t/D	F_γ			
		$\lambda = 2$	$\lambda = 6$	$\lambda = 10$	$\lambda = 15$
25°	0.25	4.42	39.78	110.50	248.63
	0.50	3.93	35.37	98.25	221.06
	0.75	3.53	31.77	88.25	198.56
30°	0.25	4.74	42.66	118.50	266.63
	0.50	4.48	40.32	112.00	252.00
	0.75	4.29	38.61	107.25	241.31
35°	0 – 1.00	5.18	46.62	129.50	291.38
40°	0.25	5.21	46.89	130.25	293.06
	0.50	5.45	49.05	136.25	306.56
	0.75	5.69	51.21	142.25	320.06
45°	0.25	5.41	48.69	135.25	304.31
	0.50	5.91	53.19	147.75	332.44
	0.75	6.30	56.70	157.50	354.38

TABLE 5 : Uplift Capacity Factors F_γ for λ = 2, 6, 10 and 15 when ϕ_b = 40°

ϕ_t	D_t/D	F_γ			
		$\lambda = 2$	$\lambda = 6$	$\lambda = 10$	$\lambda = 15$
25°	0.25	5.03	45.27	125.75	282.94
	0.50	4.26	38.34	106.50	239.63
	0.75	3.67	33.03	91.75	206.44
30°	0.25	5.37	48.33	134.25	302.06
	0.50	4.90	44.10	122.50	275.63
	0.75	4.48	40.32	112.00	252.00
35°	0.25	5.69	51.21	142.25	320.06
	0.50	5.37	48.33	134.25	302.06
	0.75	5.25	47.25	131.25	295.31
40°	0 – 1.00	6.11	54.99	152.75	343.69
45°	0.25	6.33	56.97	158.25	356.06
	0.50	6.43	57.87	160.75	361.69
	0.75	6.52	58.68	163.00	366.75

TABLE 6 : Uplift Capacity Factors F_γ for λ = 2, 6, 10 and 15 when ϕ_b = 45°

ϕ_t	D_t/D	F_γ			
		λ = 2	λ = 6	λ = 10	λ = 15
25°	0.25	5.62	50.58	140.50	316.13
	0.50	4.56	41.04	114.00	256.50
	0.75	3.81	34.29	95.25	214.31
30°	0.25	5.91	53.19	147.75	332.44
	0.50	5.15	46.35	128.75	289.69
	0.75	4.57	41.13	114.25	257.06
35°	0.25	6.25	56.25	156.25	351.56
	0.50	5.71	51.39	142.75	321.19
	0.75	5.30	47.70	132.50	298.12
40°	0.25	6.52	58.68	163.00	366.75
	0.50	6.25	56.25	156.25	351.56
	0.75	6.16	55.44	154.00	346.50
45°	0 - 1.00	6.97	62.73	174.25	392.06

horizontal strip anchors in sand behave as deep anchors. For ϕ = 45°, they suggested λ_{cr} = 9 for square and circular anchors. For horizontal strip anchors in sand for ϕ = 45°, $\lambda_{cr} = 1.5 \times 9 = 13.5$. In this work F_γ values are provided up to λ = 15, a value which is approximately selected. For loose sands (say ϕ = 30°), critical embedment depth of horizontal strip anchors in sand will be $4 \times 1.5 = 6$ (Meyerhof and Adams, 1968; Meyerhof, 1973). For $\lambda > \lambda_{cr}$ (deep anchors), the above Tables should not be used.

It is found (from Eqn.26 and Tables 2 to 6) that uplift capacity factor increases with increase in embedment ratio. For a given value of ϕ_b, ϕ_t and D_t/D, the uplift capacity factor is directly proportional to the square of embedment ratio λ.

For the similar values of ϕ_b, ϕ_t (> ϕ_b) and λ, uplift capacity factor F_γ increases with increase in D_t/D. For ϕ_b = 25°, ϕ_t = 30° and λ = 2, when D_t/D is increased from 0.0 to 1.0, uplift capacity factor increases from 3.38 to 4.25 (increase of 25.7%). Other factors being the same, this increase is found to be 106.2% for ϕ_t = 45°. From the results of uplift capacity factors for various values of ϕ_b and ϕ_t (> ϕ_b), it is observed that the increase in the value of uplift capacity factor is varying from 14.1% to 106.2% when D_t/D is increased from 0.0 to 1.0.

Other parameters being the same, uplift capacity factor increases with increase in ϕ_t. When ϕ_b = 25°, D_t/D = 0.50 and λ = 2, increase of ϕ_t from 25° to 45° results in increase of uplift capacity factor by 50.1%. For ϕ_b = 45°, D_t/D = 0.50 and λ = 2, increase of ϕ_t from 25° to 45° results in increase of uplift capacity factor by 52.8%. Similar trend was found for other values of D_t/D.

Increase in value of uplift capacity factor is observed when the value of f_b increases (other factors being the same). For example, when ϕ_t = 25°, D_t/D = 0.50 and λ = 2, increase of ϕ_b from 25° to 45° results in increase of uplift capacity factor by 34.9%. For ϕ_t = 45°, D_t/D = 0.50 and λ = 2, increase of ϕ_b from 25° to 45° shows increase in the value of uplift capacity factor by 37.5%. When a loose sand layer is overlying on the dense layer, uplift capacity factor reduces. For ϕ_b = 45°, ϕ_t = 25° and λ = 2, when D_t/D increases from 0.0 to 1.0 the uplift capacity factor decreases from 6.97 to 3.38 (51.5%).

Tables 2 to 6 can be directly made use in getting F_γ values for various cases and hence the net ultimate uplift capacity of strip anchors in layered sands can be obtained by $q_{unet} = (1/2)B\gamma F_\gamma$ and gross pull out load $P_u = q_{unet}B + W$. Thus the Tables provided are of great use in estimating uplift capacity of strip anchors in layered sands.

Summary and Conclusions

A method is proposed for the determination of passive earth force in layered sands for negative delta case using the method of slices, satisfying all the three equilibrium conditions. As an application, the problem of determination of uplift capacity of horizontal strip anchors in layered sands is solved. From the analysis carried out, the following conclusions are made.

The passive earth force obtained for $\delta/\phi = -2/3$ considering ϕ_b = 25°, 30°, 35°, 40° and 45°; ϕ_t = 25°, 30°, 35°, 40° and 45° and D_t/D = 0.0, 0.25, 0.50, 0.75 and 1.0 are reported in Table 1. The passive force obtained by the proposed method for layered sand is 2.08% to 8.11% lower than that obtained by the conventional method.

The expressions for the net ultimate uplift capacity and gross pullout load of horizontal strip anchors in layered sands are derived. The values of uplift capacity factors F_γ are obtained for various cases and are presented in the tabular form. It is found that uplift capacity factor is directly proportional to square of embedment ratio. Uplift capacity factor increases with increase in the values of ϕ_b and ϕ_t. For $\phi_t > \phi_b$, increase in the thickness of top layer results in increase in the values of uplift capacity factors. Presence of loose layer over a dense layer reduces the uplift capacity factor. The uplift capacity factors provided in Tables can be directly made use in obtaining uplift capacity of horizontal strip anchors in layered sands.

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Notations

The following notations are used:

A	=	Area of the anchor plate.
B	=	Width of the strip anchor plate.
b_i	=	Width of the i^{th} slice.
c	=	Unit cohesion of the soil.
D	=	Depth of embedment measured along the anchor rod length and also vertical height of the retaining wall.
F	=	Factor used in the inter slice friction dissipation.
F_γ	=	Uplift capacity factor.
D_t, D_b	=	Thickness of the top layer sand and bottom layer sand respectively.
$K_{p\gamma}$	=	Passive earth pressure coefficient.
N	=	Normal force on the failure surface.
N_i	=	Normal force on the i^{th} slice interface.
P_n	=	Normal component of passive earth force.
P_u	=	Gross pullout load or gross uplift load.
q_{unet}	=	Net ultimate uplift capacity
T_i	=	Tangential force on the i^{th} slice interface.
r_{bt}, r_{bb}	=	Initial length of radial line of logarithmic spiral failure surface in top and bottom layer respectively.
r_{ft},r_{fb}	=	Final length of radial line of logarithmic failure surface in top and bottom layer respectively.
W	=	Weight of the soil mass.
x_o	=	Horizontal distance of extent of failure surface at the ground level from wall face.
x_i	=	Horizontal distance from the point where failure surface meets the ground to the i^{th} slice.
α_i	=	Angle made by tangent with the horizontal at the base of i^{th} slice.
β_t, β_b	=	Angle made by final radial line with the horizontal, at its base for the top and bottom layer respectively.

δ = Angle of wall friction.

δ_i = Inter slice friction angle for i^{th} slice.

ϕ = Angle of internal friction of sand.

ϕ_t, ϕ_b = Angle of internal friction of top layer and bottom layer sand respectively.

γ = Unit weight of sand.

γ_t, γ_b = Unit weight of sand in top layer and bottom layer respectively.

θ_t, θ_b = Angle between the initial and final radial line of logarithmic failure surface in top and bottom layer of sand respectively.

λ = Embedment ratio.

λ_{cr} = Critical embedment ratio.

ω_t, ω_b = Angle made by the initial radial line of the logarithmic spiral with the horizontal in the top and bottom layer respectively.