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Increased bearing capacity and reduced settlements due to inclusions in soil

Amélioration de la capacité portante et réduction des tassements par des inclusions

Pour réaliser un léger accroissement de la capacité portante et réduire les tassements des structures construites sur des dépôts d'argiles molles, des pieux de sable ont été utilisés. Une méthode fondée sur la rupture par cisaillement est proposée pour estimer la capacité portante du sol ainsi renforcé. Les résultats de cette méthode et ceux de Hughes sont en très bonne concordance avec les résultats expérimentaux. Les effets des inclusions sur le tassement sont également étudiés à l'aide de la méthode des éléments finis.

INTRODUCTION

Soft clay deposits require improvement of their properties if they have to be utilized as foundations. One of the ways to improve the soil is to reinforce it with gravel or sand piles. In addition to reinforcing and improving the strength and deformation properties, granular piles act as drains through which excess pore water pressure of the soft soil can dissipate easily. Performance of granular piles in soft clay has been reported in (1,2,7,8). However, the design and analysis of granular piles reinforced soft clays is still based mostly on semi-empirical methods. An attempt has been made to present in two separate parts (A) rational methods for estimating bearing capacity and (B) settlement of granular pile reinforced soft clay.

A. BEARING CAPACITY

Three modes of failure are possible for the composite reinforced soil system, viz., (i) bulging (ii) side shear and end bearing and (iii) general shear failures. Hughes and Withers (4,5) have observed bulging failure of granular piles and estimate its bearing capacity, as

$$q_{ult} = \frac{1 + \sin \phi_1}{1 - \sin \phi_1} (\sigma'_{ro} + 4C_2) \qquad (1)$$

where C_2 is the undrained cohesion of the soft soil, ϕ_1 - angle of shearing resistance of pile material, σ'_{ro} - the initial lateral stress over the length of the pile. This analysis is valid only when the ratio of the diameters of the pile and loaded area is unity. The analysis based on pile type failure predicts the ultimate load as

$$Q_{ult} = f_s A_s + q_b A_b \qquad (2)$$

where A_s and A_b are respectively the surface and base areas of the pile, f_s is adhesion between the soil and the pile material, and q_b is the base resistance.

In general, granular piles have low stiffness compared to rigid piles and can undergo large lateral displacements. As such it is reasonable to consider the third mode of failure, viz., general shear failure in developing rational analysis for estimating the strength of the reinforced soil system.

The analysis of general shear failure of a medium is made for the plane strain case. Accordingly the soft and weak clay is assumed to be reinforced by a long trench and the bearing capacity of the composite medium estimated. For axisymmetric case, i.e., granular piles, the equation is modified by incorporating shape factors (9). The upper bound theorem of limit analysis based on kinematic considerations is used (Fig.1). The width of the strip load and the trench are respectively B and d_p. The sum of internal energies mobilized along various failure surfaces, the work done by the weight of the soil and the surcharge, is equated to the work done by the external load. Internal energy dissipated because of cohesion along the failure surfaces, work done on account of weight of soil because of surcharge, and external load q_{ult} can be expressed in terms of cohesion, angle of shearing resistance, unit weights of soil and pile materials, ratio $d_{p/B}$, and wedge angles ξ and η (6). Finally q_{ult} is expressed

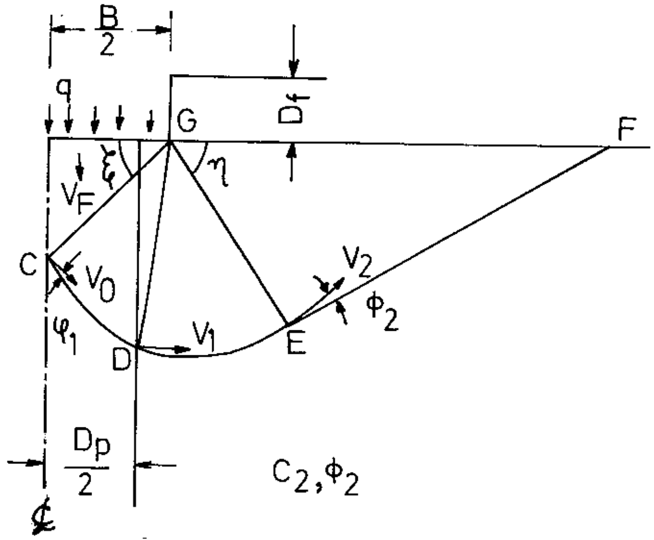

FIG.1.- FAILURE MECHANISM FOR GRANULAR PILE SOIL SYSTEM

similar to Terzaghi's equation as

$$q_{ult} = C_2 N_C + \frac{\gamma_2 B}{2} N_\gamma + \gamma_2 D_f . N_q \qquad (3)$$

in which
$$N_C = \frac{C_1}{C_2} N_{C_1} + N_{C_2} \qquad (4)$$

$$N_\gamma = \frac{1}{2}(N_{\gamma_1} + N_{\gamma_2}) \qquad (5)$$

C_1 and γ_1, and C_2 and γ_2 are cohesion and unit weight of pile and soft soil respectively, and D_f - the depth of foundation, N_{C1}, N_{C2}, $N_{\gamma 1}$, $N_{\gamma 2}$ and N_q are dimensionless bearing capacity factors which depend on properties of pile and soil materials and the ratio $d_{p/B}$. These bearing capacity factors need to be minimized with respect to wedge angles ξ and η, i.e.,

$$\frac{\partial q_{ult}}{\partial \xi} = 0 \quad \text{and} \quad \frac{\partial q_{ult}}{\partial \eta} = 0 \qquad (6)$$

Because of the complexity of the expression for q_{ult} it is preferred to minimize the bearing capacity factors separately. The error involved is less than 2 percent. In optimization technique using Davidon-Fletcher-Powel method (3) is used to get the minimum bearing capacity factors for the composite soil-granular pile system.

Modified Hughes Approach

As stated earlier Hughes approach for predicting ultimate bearing capacity for granular pile reinforced soil is limited to case where the ratio $d_{p/B} = 1$. The same theory can be modified for $d_{p/B}$ less than 1 as follows

$$q_{ult} = \frac{1+\sin \phi_1}{1-\sin \phi_1} (4c_2 + \sigma'_{ro} + k_o q_s) - \frac{d_p^2}{B^2} + \left(1 - \frac{d_p^2}{B^2}\right) q_s \qquad (7)$$

where q_s is the bearing capacity of soft soil expressed as = (2/3) $c_2 N_c$ and k_o coefficient of earth pressure at rest. With this modification Hughes approach becomes general and applicable to any ratio of $d_{p/B}$ in the range of 0 to 1.

Experimental Studies

In order to verify the present theory some experiments were carried out in laboratory using local clayey silt (PI = 10, LL = 25, sand = 10 percent, silt = 75 percent, clay = 15 percent), dry unit weight of 1.5 gm/cc., moisture content of 28 percent, corresponding to undrained strength parameters of c_u = 0.052 kg/cm^2 and ϕ_u = 0. Size of mould in which tests were done was 15 cm. diameter and 17.5 cm. high. Granular piles $d_{p/B}$ = 0.5 and 1 were installed and tested with the footings of diameters 2.5 and 5.0 cm. Length of the granular pile was 4 times its diameter. Sand used in the pile has a unit weight of 2.0 gm/cc. Load settlement curves were obtained for such soft soil reinforced with a granular pile. Ultimate bearing capacity is estimated from the experimental results as the intensity of load at settlement equal to B/4.

Results

Bearing capacity charts for N_c, N_γ, and N_q for various range of parameters such (c_1/c_2), (γ_1/γ_2) and $d_{p/B}$ for reinforced soil system are presented in Fig.2 through 4. The charts presented are similar to those for homogeneous soil. For $d_{p/B}$ = 0 the bearing capacity factors by the present analysis are identical to those given by Terzaghi for homogeneous soil. As the ratio $d_{p/B}$ increases, more and more stronger material reinforces the soft soil and bearing capacity factors N_c, N_γ and N_q increase. For the c_1/c_2 = 0 when $d_{p/B}$ changes from 0 to 1, the percentage increase in N_c is of the order of 80% for $\phi = 30^\circ$ and 300% for $\phi = 40^\circ$, percentage increase in N_q value is 260% for $\phi = 30^\circ$ and 475% for $\phi = 40^\circ$ respectively. N_γ increases from 0 to 3.3 for ϕ=30° and 7.6 for $\phi = 40^\circ$ for $d_{p/B}$ = 1.0 and γ_1/γ_2 = 1.0. Percentage increase in bearing capacity factors will be still higher ϕ values of pile material. For intermediate values of c_1/c_2 and γ_1/γ_2 and ϕ_1 the values can be interpolated.

The various theories are compared with measured experimental results. The ultimate bearing capacity is estimated using equations 2,3 and 7 and substituting the

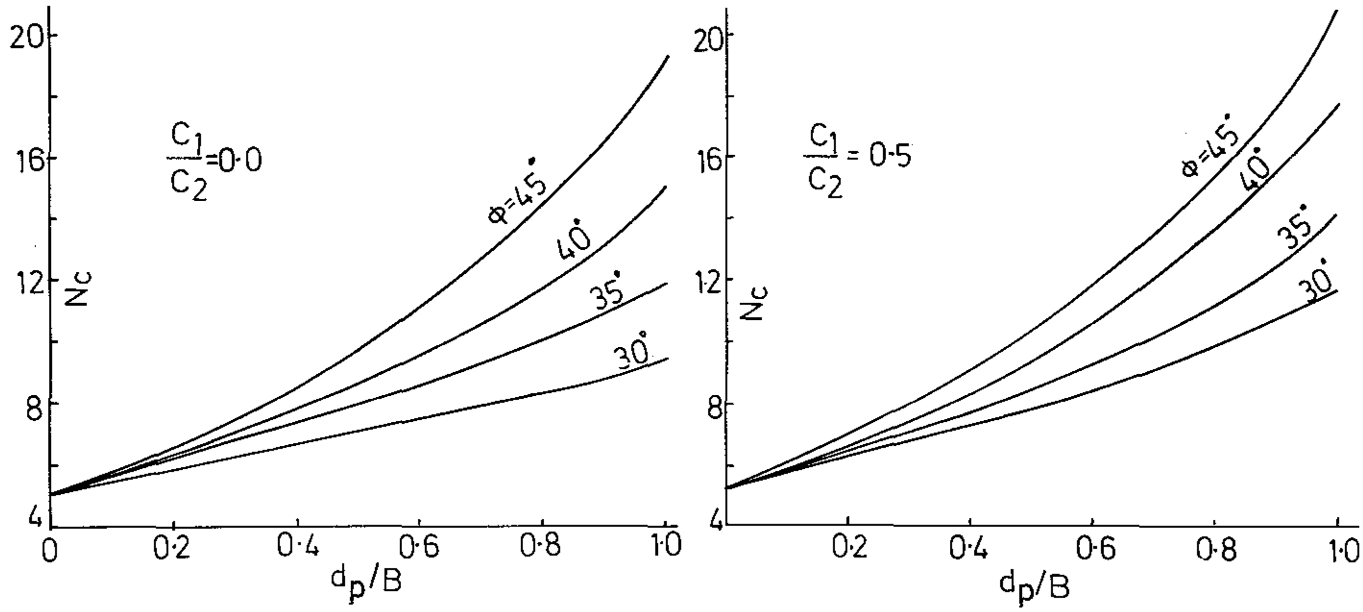

FIG. 2.- N_C - VALUES

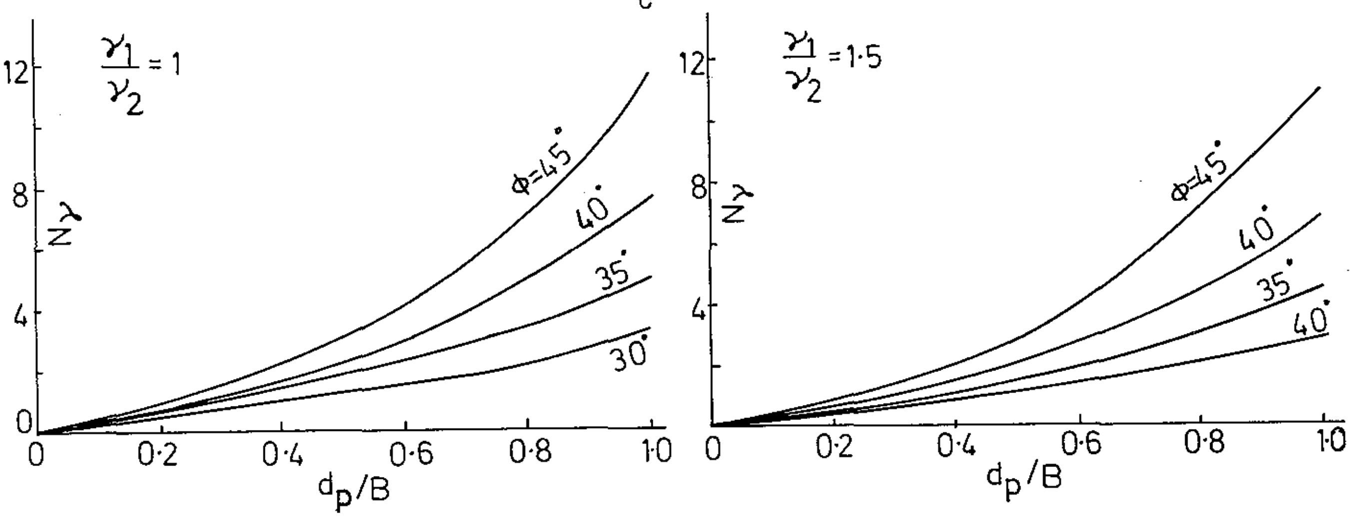

FIG. 3.- N_γ - VALUES

appropriate values for the various parameters as given in Table 1. The calculated values are compared with the measured results in Table 1. It is seen that the predictions by the Modified Hughes's approach and the present analysis agree well with the measured values.

B. REDUCTION IN SETTLEMENT

When soft ground is improved by a large number of granular piles, the carrying capacity is not only improved by the ability of reinforcing elements to transfer the load to deeper stiffer soils but also by the stiffenning of the soft soil by the prevention of lateral and downward displacements. Settlement of a loaded area ringed by granular piles is estimated. The problem is converted to that of a loaded area confined by a cylindrical membrane.

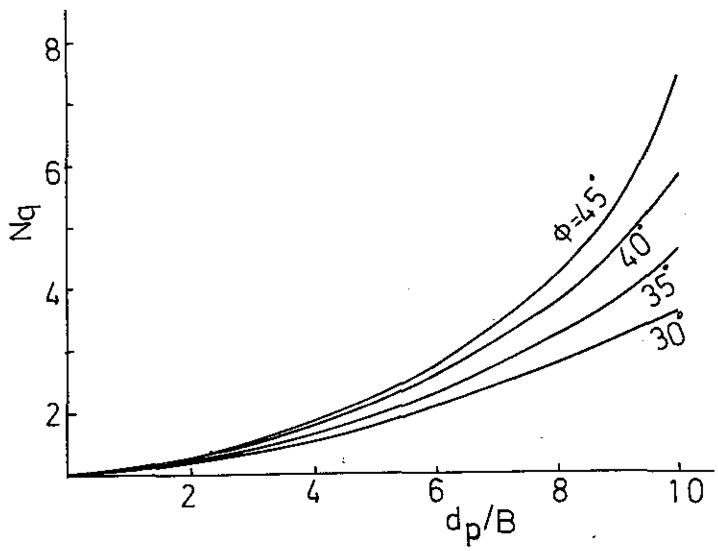

FIG. 4.- N_q - VALUES

TABLE 1.- COMPARISON OF ULTIMATE BEARING CAPACITY BY DIFFERENT ANALYSES AND EXPERIMENTAL RESULTS.

$C_1 = 0$
$\phi_1 = 30^\circ$ and 40°
$\gamma_1 = 2.0$ gms/cc
Moisture content = 28 %

Pile $C_2 = 0.052$ kg/cm^2 $\phi_2 = 0$
$\gamma_2 = 1.5$ gm/cc
q_{ult} in kg/cm^2
Length of column = 4 d_p

d_p/B	Present Analysis q_{ult} for $\phi = 30^\circ$	Increase	Present Analysis q_{ult} for $\phi = 40^\circ$	Increase	Modified Hughes Analysis q_{ult} for $\phi = 30^\circ$	Increase	Modified Hughes Analysis q_{ult} for $\phi = 40^\circ$	Increase	Pile Analysis q_{ult}	Experimental q_{ult}	Experimental Increase
0	0.205		0.205		0.205		0.205			0.196	
0.25	0.394	92	0.462	125	0.278	36	0.323	58			
0.50	0.497	142	0.634	208	0.497	142	0.678	230	0.692	0.462	135
1.0	0.802	291	1.304	536	0.894	346	1.374	570	2.020	0.812	312

Fig.5 shows the geometry of the problem. A uniformly loaded area of diameter D is confined by a ring of piles of thickness D_p, inner radius, D_r, length L, and modulus of elasticity, E_p. A finite soil layer of thickness, H is considered. The finite element method using isoparametric quadrilateral elements is employed to get the settlements.

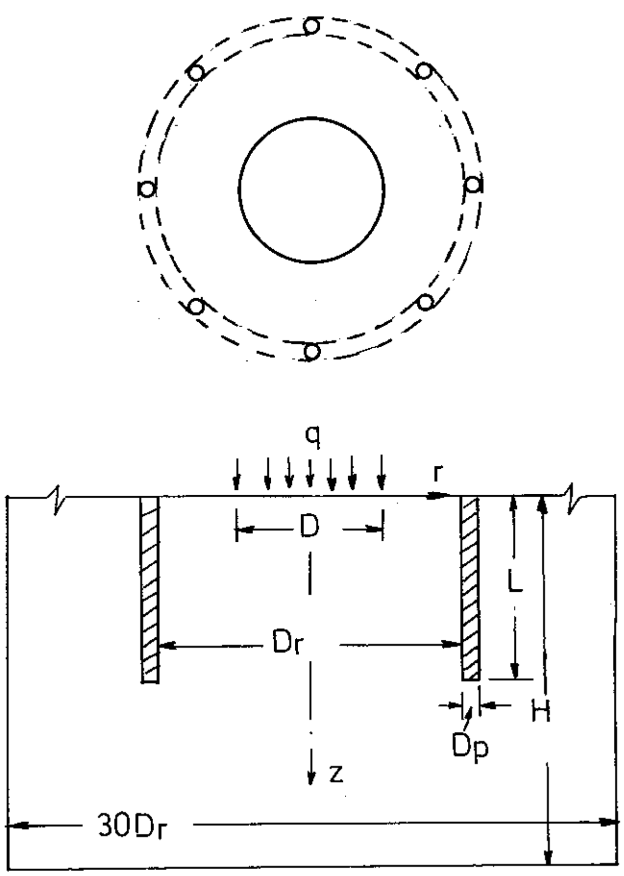

FIG.5.- GEOMETRY OF INCLUSION-SOIL SYSTEM

Results

Numerical investigation has been done on IBM 7044 computer. The results are presented in terms of Settlement Reduction Factor (S_ρ) defined as

$$S_\rho = \frac{\rho_p}{\rho_{wp}} \qquad (12)$$

where ρ_p - settlement of central point in the presence of pile
ρ_{wp} - settlement of central point without pile

Table 2 gives the variation in settlement reduction factor with (D_r/D_1) with other

TABLE 2.- VARIATION OF S_ρ WITH D_r
($D_r/D_p = 7.5$. $L/D_p = 20$, $E_p/E_s = 50$, $H/D_p = 80$
$\nu_p = 0.2$, $\nu_s = 0.4$)

D_r/D_1	1	3	5	10
S_ρ	0.820	0.829	0.786	0.648

variables kept constant. It can be seen that the effect of piles is felt even when they are at a great distance from the loading surface.

Table 3 shows the variation of S_ρ for various values of (L/D_p). It is observed

TABLE 3.-VARIATION OF S_ρ WITH LENGTH OF THE PILE
($D_r/D_p = 7.5$, $D_r/D_1=3$, $E_p/E_s=50$, $H/D_p=80$,
$\nu_p = 0.2$, $\nu_s = 0.4$)

L/D_p	10	20	30	40
S_ρ	0.850	0.829	0.813	0.803

that the settlement reduction does not vary uniformly with increase in the length of the pile. The settlement reduction increases from 15 to 19.7 percent when the pile length is increased from 10 D_p to 30 D_p, but this reduction is only is 1 percent when the length is increased from 30 D_p to 40 D_p.

Table 4 indicates that here stiffness of the pile has a considerable effect on the

TABLE 4.- VARIATION OF S_ρ WITH PILE STIFFNESS

(D_r/D_p = 7.5, D_r/D_1 = 3.0, L/D_p = 20, H/D_p = 80, ν_p= 0.2, ν_s = 0.4)

E_p/E_s	2	5	10	50	100	500
S_ρ	0.926	0.892	0.857	0.829	0.816	0.810

Settlement Reduction Factor (SRF) more so for low values of (E_p/E_s). The variation is asymptotic with increase in E_p/E_s.

Table 5 shows the variation of SRF with E_p/E_s and L/D_p.

TABLE 5.- VARIATION OF S_ρ WITH (L/D_p) AND (E_p/E_s)

(D_r/D_p = 7.5, D_r/D_1=3.0, H/D_p= 80, ν_p = 0.2 ν_s = 0.4)

L/D_p \ E_p/E_s	50	100	500	1000	2000
	Variation of S_ρ				
10	.850	.842	.840	.838	.837
20	.829	.816	.810	.806	.805
30	.813	.808	.795	.793	.792
40	.803	.799	.790	.789	.788

CONCLUSIONS

Analysis has been proposed for granular pile reinforced soft clay and the results compared with the existing approaches and experimental studies. The values of ultimate bearing capacity predicted by the present theory are close to those predicted by Modified Hughes's approach and the experimental results. The pile formula predicts higher strengths. Increase in strength by reinforcing the soft soil is remarkable and it confirms the findings of earlier researchers. A parametric study has been made and design charts for bearing capacity factors presented. Knowing the ratios of c_1/c_2, γ_1/γ_2 and d_p/B and $\emptyset_1$ and $\emptyset_2$ values, the new bearing capacity factors can be obtained from the charts, and the ultimate bearing capacity of soft soil reinforced with granular pile predicted. This study reveals that settlements are reduced in the presence of piles surrounding a loaded area.

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