Settlement Analysis of Partially Penetrated Granular Piles in Lightly Over Consolidated Soils

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1. Introduction

Granular Piles (GPs) are composed of compacted sand or gravel installed into soft ground often by displacement method. The ground improvement by GPs that leads to composite reinforced ground has become a most popular technique through out the world. However, in some instances, it is not feasible to extend the GPs up to the full depth of a deep soft soil layer technically and economically. In some other cases, where soil becomes stiffer with depth the full penetration of GP is not necessary to achieve the required degree of improvement. The settlement analysis is being carried out for partially penetrated GP reinforced ground mechanistically using 1-D compression equation for lightly over consolidated (LOC) clayey soil based on the unit cell concept. Numerical evaluations are made to illustrate the influences of various design parameters such as (i) relative length of GP to depth of unit cell i.e. degree of penetration of GP, (ii) spacing of GP (iii) over-consolidation ratio (iv) relative stiffness of GP.

2. Problem Definition and Method of Analysis

The unit cell of diameter, d_e and depth, H, consisting GP of length, L and diameter, d, is loaded with a uniform vertical load, q_o (Fig. 1). The GP is assumed to behave as a linearly deformable material defined by a modulus of deformation, E_{gp}. The soil is assumed to be homogeneous characterized by the compression index, C_c, initial void ratio, e_o, and saturated unit weight, γ_s. Water table is located at the ground level. An incompressible crust of thickness equal to 0.05H having unit weight, 1.25 times of γ_s is assumed. The unit cell is divided into a number of layers of equal thickness $\Delta H = H/n$ and the solution is obtained by applying compatibility of displacements of the GP and the soil at the top.

For a stress increment, q, that leads into NC region of the soil i.e. $\sigma'_o + q > \sigma'_c$ or $q > \sigma'_o(OCR-1)$ (Fig. 2), the settlement of a layer of thickness, ΔH , is given by

$$\Delta S_i = \left(\frac{C_S}{1+e_o} \log \frac{\sigma'_c}{\sigma'_o} + \frac{C_c}{1+e_o} \log \frac{\sigma'_o + q}{\sigma'_c} \right) \Delta H \tag{1}$$

and for an stress increment contained within the OC region i.e. $\sigma'_o + q < \sigma'_c$ or $q < \sigma'_o(OCR-1)$ (Fig. 2), the settlement is

$$\Delta S_i = \left(\frac{C_S}{1+e_o} \log \frac{\sigma'_o + q}{\sigma'_o} \right) \Delta H \tag{2}$$

The compression of GP, is

$$\Delta S_{gp} = \frac{q_{gp} L}{E_{gp}} \tag{3}$$

All the stresses and E_{gp} are normalized with respect to $\gamma_s H$ and all the dimensions and settlements with respect to H. The final settlements of GP, S^*_{gp}, treated ground, S^*_{tr} and untreated ground, S^*_{untr} are obtained by using the above equations for different layers and summing up.

$$S^*_{gp} = \frac{C_c}{1+e_o} \left\{ \frac{q^*_{qp} L^*}{E^*_{gp} \dfrac{C_c}{1+e_o}} + \sum_{i=n_c}^{n} \begin{matrix} \left(\dfrac{C_s}{C_c} \log OCR + \log \dfrac{\sigma'^*_{o_i} + q^*_{gp}}{\sigma'^*_{o_i} OCR} \right) \Delta H^* \\ or \\ \left(\dfrac{C_s}{C_c} \log \dfrac{\sigma'^*_{o_i} + q^*_{gp}}{\sigma'^*_{o_i}} \right) \Delta H^* \end{matrix} \right\} \tag{4}$$

$$S^*_{tr} = \frac{C_c}{1+e_o} \left\{ \frac{q^*_c L^*}{E^*_{gp} \dfrac{C_c}{1+e_o}} + \sum_{i=c}^{n} \begin{matrix} \left(\dfrac{C_s}{C_c} \log OCR + \log \dfrac{\sigma'^*_{o_i} + q^*_c}{\sigma'^*_{o_i} OCR} \right) \Delta H^* \\ or \\ \left(\dfrac{C_s}{C_c} \log \dfrac{\sigma'^*_{o_i} + q^*_c}{\sigma'^*_{o_i}} \right) \Delta H^* \end{matrix} \right\} \tag{5}$$

$$S^*_{untr} = \frac{C_c}{1+e_o} \left\{ \frac{q^*_o L^*}{E^*_{gp} \dfrac{C_c}{1+e_o}} + \sum_{i=c}^{n} \begin{matrix} \left(\dfrac{C_s}{C_c} \log OCR + \log \dfrac{\sigma'^*_{o_i} + q^*_o}{\sigma'^*_{o_i} OCR} \right) \Delta H^* \\ or \\ \left(\dfrac{C_s}{C_c} \log \dfrac{\sigma'^*_{o_i} + q^*_o}{\sigma'^*_{o_i}} \right) \Delta H^* \end{matrix} \right\} \tag{6}$$

where superscript * denotes the normalized form of the parameters. The settlement ratio, β once again is

$$\beta = \frac{S^*_{tr}}{S^*_{untr}} \tag{7}$$

A general program is developed to solve these equations.

Key Words: Granular Piles, Partial Penetration, Settlement Analysis, Over Consolidation Ratio.
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3. Results and Discussion

The settlement reduction ratio, β, is dependent on several parameters (Eq. 7), predictions are made varying these design parameters.

- Degree of Penetration of GP: Fig. 3.3a depicts the variation of settlement ratio, β, with the applied load intensity, q_o^*, for different values of L^*. GPs installed over only 50% depth of the deposit show a continuous increase of the settlement ratio, β, the value increasing from 0.672 for q_o^* equal to 0.25 to 0.787 for q_o^* equal to 2.0. With increasing degree of penetration, L^*, of GPs, the rate of increase of β with q_o^* decreases in the applied stress range of 0.25 to 0.5. The settlement ratio, β, is nearly constant at 0.48 for $L^* = 0.8$ while it decrease slightly for $L^* > 0.8$ (i.e. for values of 0.9 and 1.0) in the stress range 0.25 to 0.5.
- Spacing of GPs: Settlement ratio, β, increases linearly with increase in q_o^* for q_o^* greater than 0.5 for all the values of A_r (Fig. 3.3b). But for lower values of q_o^* where the over consolidation effect is significant, the curves are of different trends. For very low value of A_r, 0.05, β decreases slightly with q_o^* from 0.798 at $q_o^* = 0.25$ to 0.796 q_o^* at = 0.75 and increases to value 0.877 at $q_o^* = 2.0$.
- Over Consolidation Ratio: For normally consolidated ground (OCR = 1.0), settlement ratio, β, increases linearly with q_o^* from 0.407 at $q_o^* = 0.25$ to 0.574 at $q_o^* = 2.0$. For $q_o^* > 1.0$, β increases linearly with q_o^* for all the values of OCR (Fig. 3.3c). The response is irregular for $q_o^* < 1.0$ e.g. β increases with q_o^* from 0.428 at $q_o^* = 0.25$ to a value 0.572 at $q_o^* = 0.75$, after decreasing to value 0.570 at $q_o^* = 1.0$, again increases to value 0.636 at $q_o^* = 2.0$.
- Relative Stiffness of GP: The value of $K_{gp} = E^*_{gp}\dfrac{C_c}{1+e_o}$ influences the sharing of stress by GP and thus the settlement of the composite ground. The curves for two extreme values of K_{gp} considered (K_{gp} = 2.5 and 300) have anti-symmetric trends (Fig. 3.3d). β increases from 0.89 at $q_o^* = 0.25$ to 1.00 at $q_o^* = 2.0$ for $K_{gp} = 2.5$ while it decreases from 0.348 at $q_o^* = 0.25$ to 0.319 at $q_o^* = 2.0$ for $K_{gp} = 300$.

4. Concluding Remarks

The response of the partially penetrated GP reinforced ground is predicted in terms of settlement ratio, β. As to be expected, settlement ratio, β, decreases with increase in value of degree of penetration, L^*, area ratio, A_r, relative stiffness of GP, K_{gp} and decreases with decrease in value of OCR. Settlement ratio, β, increases with the applied load intensity, q_o^*, for q_o^* > 0.5 for all the degrees of penetration of GPs but in applied stress range of 0.25 to 0.5, settlement ratio increases with q_o^* for $L^* = 0.5$ and it decreases for $L^* = 1.0$. At lower stress levels, these different types of trends are also shown by other non-dimensional parameters. However, in the present study, only the simplest possible case, OCR constant with depth is considered. A further study may be carried out by varying the OCR with depth to predict the response of more ground conditions.

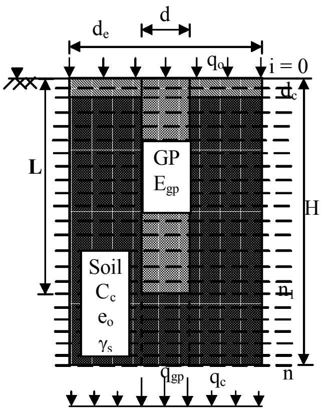

Fig. 3.1 Definition Sketch

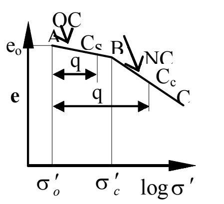

Fig. 3.2 e- logσ′ relation.

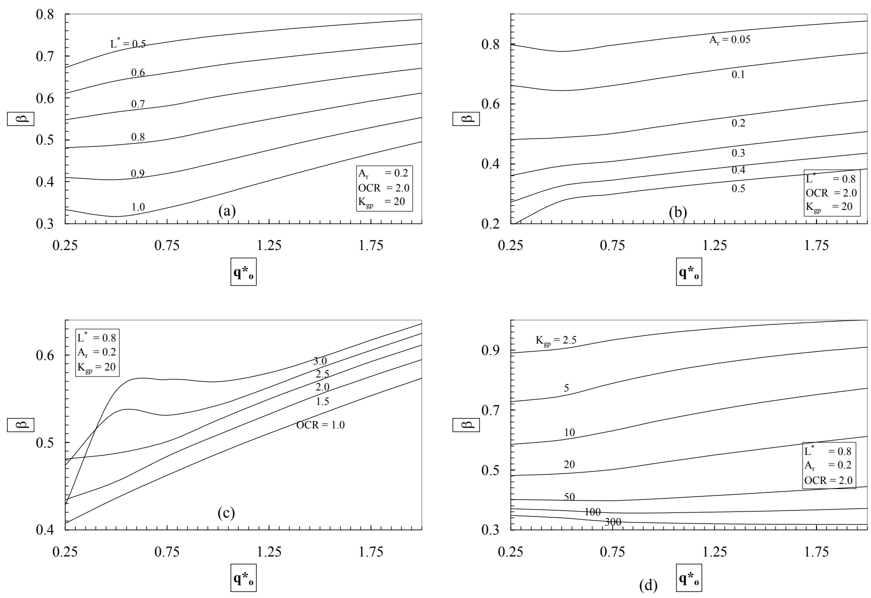

Fig. 3.3 Variation of β with q^*_o – Effect of (a) L^*, (b) A_r, (c) OCR and (d) K_{gp}.