Group interaction analysis of displacements in granular pile anchors (GPA)

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ABSTRACT

Granular piles improve the behavior of the ground by increasing bearing capacity, reducing settlements, accelerating consolidation, and mitigating liquefaction related damages by reinforcement and densification effects. GPAs due to their inherent nature can resist compressive and shear loads but not tensile ones. Granular piles can be made to resist pullout or uplift forces by placing an anchor at the base and attaching the same by a cable or rod to the footing to transfer the applied pullout forces to the bottom of the GP. Such an assembly is termed a Granular Pile Anchor (GPA). Analyses for displacements in granular pile anchors in groups of two, three or four, are presented based on Poulos and Davis (1980) for rigid piles. Results are presented as variations of interaction factor, ‘α’ with spacing $s/d$ and relative stiffness factor, $K$. The results compare well with those of Poulos and Davis for rigid piles. The principle of superposition is validated for groups of 3 and 4 GPA.

Keywords: Group interaction, uplift, granular pile/stone column, ground-GPA interaction, linear response.

1 INTRODUCTION

Granular piles improve bearing capacity of foundations and stability of embankments founded on soft ground, reduce settlements, increase the time-rate of consolidation and mitigate liquefaction related damage by reinforcement and densification effects. The utility of the granular piles is restricted as they can only transfer compressive loads of foundations to the ground and resist shear stresses.

Pullout or tensile forces applied on the granular piles can be resisted by a simple modification of placing an anchor at the base and attaching the same by a cable or rod to the footing to transfer the applied pullout force to the bottom of the GP. Such an assembly is termed a Granular Pile Anchor (GPA). Phani Kumar (1997) reported tests on model granular pile anchors to control heave in expansive soils. White et al. (2001) studied the application of reinforced geopiers for resisting tensile loads and settlement control. Lillis (2004) reported results from in situ tests on pullout response of GPA. Kumar et al. (1997 & 1999) and Ranjan et al. (2000) present results from laboratory and field tests on pullout response of GPA in cohesive and cohesionless soils. A linear analysis of displacements of GPA is presented by Madhav et al. (2008).

2 PROBLEM DEFINITION

A group of two granular pile anchors each of length, $L$, and diameter, $d$, spaced at centre to centre distance, $s$, with the soil and pile material characterized by moduli of deformation, $E_s$ and $E_{gp}$, and unit weights, $\gamma_s$ and $\gamma_{gp}$, respectively is considered (Fig.1). Poisson’s ratio of the soil is $\nu_s$. Forces, $P_o$, applied at the bases of the two GPA are resisted by the shear stresses, $\tau$, acting along the peripheries of the piles (Fig. 2). The group action of the GPA due to the pullout loads is analyzed by incorporating the influence of one GPA on the other in terms of displacements. The GPA surface is divided into ‘n’ elements of length, $\Delta L (=L/n)$. The stress acting on a typical element, $i$, is $\tau_i$. The displacement at the centre of an element, $i$, due to stresses acting on element, $j$, are obtained by the method described by Poulos and Davis (1980).

Fig. 1 GPA under Pullout
Integrating numerically, Mindlin’s equation (1936) for point load in the interior of a semi-infinite elastic continuum over the cylindrical periphery of the element, the displacement, $\rho_{s,i}$, of the soil adjacent to the centre of the $i$th element due to stress, $\tau_j$, acting on the element, $j$, for GPA1 is

$$\rho_{s,i} = \frac{d}{E_s} \int_{s_i}^{s_j} \tau_j \, dz$$

where $\rho_{s,i}$ is the soil displacement influence coefficient for GPA1. Total soil displacement, $\rho_{s,ij}$, adjacent to node ‘i’ due to stresses on all the elements of the GPA, is obtained by summing the displacements at node ‘i’, due to stresses on elements $j=1$ to $n$, as

$$\rho_{s,ij} = \frac{d}{E_s} \sum_{j=1}^{n} \int_{s_i}^{s_j} \tau_j \, dz$$

Soil displacements of all the nodes due to the shear stresses mobilized on it are collated to arrive at

$$\{\rho_s\} = \frac{d}{E_s} \{I_s\} \{\tau\}$$

where $\{\rho_s\}$ and $\{\tau\}$ are respectively the soil displacement and shear stress vectors of size, $n$, and $\{I_s\}$ is the soil displacement influence coefficient matrix of size $n \times n$. The displacements generated in the first GPA due to shear stresses around the second GPA are estimated in terms of the relative spacing, $s/d$. Total soil displacements, $\rho_{sg,ij}$, due to stress, $\tau_j$, on the $j$th elements of the first & the second GPA, are obtained by summing up all the displacements at node ‘i’, due to stresses on elements $j=1$ to $n$. The total displacements of the nodes, $\rho_{SG,ij}$, in GPA1 due to the loading on itself and the loading on GPA2 are the sum of the displacements due to both the loadings as

$$\{\rho_{SG,ij}\} = \frac{d}{E_s} \{I_{SG,ij}\} \{\tau\}$$

The elements of matrix $\{I_{SG,ij}\}$ are the coefficients of influence of stresses acting on the GPA2 on to those of the first one. The displacements in a simplified form are

$$\{\rho_{SG2}\} = \frac{d}{E_s} \{I_{SG2}\} \{\tau\}$$

where $\{\rho_{SG2}\}$ is a vector of displacements and $\{I_{SG2}\}$ is the soil displacement influence coefficient matrix of size, $n \times n$ representing the sum of the influence coefficients of GPA1 and GPA2.

### 2.1 DISPLACEMENTS OF GPA

The vertical displacements of a GPA are obtained considering it to be a compressible pile. Figure 3 depicts the stresses on an infinitesimal element of GPA of thickness, $\Delta z$. Poulos and Davis (1980) have established that lateral/radial stresses have negligible effect on the vertical displacements.

The equilibrium of forces in the vertical direction reduces to

$$\frac{d\sigma_z}{dz} - \frac{4}{d} \tau = 0$$

where $\sigma_z$ is the normal stress in the GPA. The stress-strain relationship for the GPA material, is

$$\sigma_z = E_{gp} e_z = E_{gp} \frac{d\rho_{gp}}{dz}$$

where $\Delta z$ and $\rho_{gp}$ are respectively the axial strain and GPA displacement. For GPA with constant $E_{gp}$ Eqs. 6 & 7 are combined to get

$$E_{gp} \frac{d^2\rho_{gp}}{dz^2} - \frac{4}{d} \tau = 0$$

Eq. 8 is solved along with the boundary conditions, viz., at $z = 0$ (i.e. at the top of GPA) $P=0$ (free boundary) and at $z = L$ (tip of the GPA), $P=P_0$ (the applied load). Since Eq. 8 cannot be integrated directly, a numerical (finite difference) approach is adopted. Eq. 8 in finite difference form becomes

$$\frac{\sigma_z + \Delta\sigma_z}{\sigma_z} = \frac{d}{E_s} \frac{d\rho_{s}}{dz}$$

Fig. 3 Stresses acting on an Infinitesimal Element
\[
\frac{\rho_{gp,i+1} - 2\rho_{gp,i} + \rho_{gp,i-1}}{(\Delta L)^2} - \frac{4}{E_{gp}}d\tau_i = 0 \quad (9)
\]

where \(\rho_{gp,i}\) and \(\tau_i\) are respectively the displacement at the centre of node 'i' and the shear stress on the interface of element, 'i', of the GPA. Eq. 9 can be written directly for nodes i = 2 to (n-1). Invoking the first boundary condition, \(P = 0\), i.e., \(\sigma_x = 0\) and hence \(e_x = 0\) leads to

\[
\rho_{gp,1} = \rho_{gp,1} \quad (10)
\]

where \(\rho_{gp,1}\) is the displacement at the imaginary node 1' above the GPA. Eq. 8 can now be written for node 1 as well. All the equations for nodes 1 to (n-1) are collated and written as

\[
[I_{gp}]\rho_{gp} - \frac{4L^2}{E_{gp}n^2d}[\tau] = 0 \quad (11)
\]

where \([I_{gp}]\) is the GPA displacement influence coefficient matrix, of size nx(n-1). The compatibility of displacements requires

\[
\rho_s = \rho_{gp} \quad (12)
\]

Combining Eqs. 5, 11 & 12 and simplifying,

\[
\left([I_{gp}]d[I_{s21}] - \frac{4L^2}{E_{s}n^2d}[\tau]\right)[\tau] = 0 \quad (13)
\]

The analysis of a two GPA group is therefore identical to that of a single GPA, except that the soil-displacement influence matrix includes contributions from the second GPA. The 'Interaction factor', for two group GPA is expressed as \('\alpha_{G2}\'\) (Poulos and Davis 1980) written as.

\[
\alpha_{G2} = \frac{\text{Additional Settlement caused by adjacent GPA}}{\text{Settlement of GPA under its own load}} \quad (14)
\]

2.2 GROUP OF THREE GPA

The analysis of group of three GPAs (Fig. 4) is similar to that of the group of two GPA except for the additional displacements due to the loading in the third adjacent GPA. The total displacements in a given GPA are the sum of the displacements generated due to the loading on the GPA itself and displacements due to the loading on the two adjacent GPAs located identically at a spacing 'S'.

The displacements due to loads on second GPA, \(\rho_{s21}\), and third GPA, \(\rho_{s31}\), at node 'i' due to stresses acting on all the elements of the GPA2 and GPA3, \(j=1\) to \(n\) respectively are obtained by summing up the displacements at node 'i', due to stresses acting on all the elements in vector form written as the vertical soil displacements \(\rho_{s21}\) and \(\rho_{s31}\)

\[
\rho_{s21} = \frac{d[I_{s21}]}{E_s}[\tau] \quad \text{and} \quad \rho_{s31} = \frac{d[I_{s31}]}{E_s}[\tau] \quad (15)
\]

where \(\rho_{s21}\) and \(\rho_{s31}\) are respectively the displacement at the imaginary node 'i' and the shear stress on the interface of element, 'i', of the GPA. Eq. 9 can be written directly for nodes i = 2 to (n-1). Invoking the first boundary condition, \(P = 0\), i.e., \(\sigma_x = 0\) and hence \(e_x = 0\) leads to

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\rho_{gp,1} = \rho_{gp,1} \quad (10)
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where \(\rho_{gp,1}\) is the displacement at the imaginary node 1' above the GPA. Eq. 8 can now be written for node 1 as well. All the equations for nodes 1 to (n-1) are collated and written as

\[
[I_{gp}]\rho_{gp} - \frac{4L^2}{E_{gp}n^2d}[\tau] = 0 \quad (11)
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\[
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\rho_{s21} = \frac{d[I_{s21}]}{E_s}[\tau] \quad \text{and} \quad \rho_{s31} = \frac{d[I_{s31}]}{E_s}[\tau] \quad (15)
\]
diagonally. Two GPA are at a spacing of ‘S’ while the
fourth one is a distance of ‘√2S’ diagonally from GPA1.

As GPA2 & GPA3 are spaced equally from GPA1
their contributions to displacements of GPA1 are equal.
Displacements for a group of four GPA in matrix form

\[
[p_{GPA4}]=d \frac{d}{E_t} \begin{bmatrix} l_{SG4} \\ \end{bmatrix} \text{ for } \alpha_{GPA4} \text{ in a group of four.}
\]  

(21)

where \([l_{SG4}]=l_{GPA1}+2l_{GPA2}+l_{GPA3}\) is the soil displacement
influence coefficient matrix of size, \(n \times n\) representing
the sum of the influence coefficients of GPA1, GPA2,
GPA3 and GPA4. Considering the compatibility of
displacements Eq. 22 is written as

\[
\left\{ l_{SG4} \right\} = \frac{4L^2}{E_g n^2 d} \left\{ \begin{array}{c} 0 \\ 0 \\ 0 \\ 0 \\ \vdots \\ 0 \end{array} \right\}
\]

(22)

The interaction factor, \(\alpha_{GPA}\) for a GPA in a group of
four is defined as

\[
\alpha_{GPA} = \frac{\text{Additional settlement caused by all adjacent GPA in group}}{\text{Settlement of GPA under its own load}}
\]

(23)

Based on the superposition principle for the interaction
factor obtained for two GPA group, the interaction
factor for group of four GPA is

\[
\alpha_{GPA} = 2 \alpha_{GPA} \text{ (for spacing, } S) + \alpha_{GPA} \text{ (for spacing, } \sqrt{2}S) \]

(24)

The interaction factors, \(\alpha_{GPA}\) obtained from both the
methods are compared under the influence of vari
ous parameters similar to the group of two GPA.

3 RESULTS AND DISCUSSIONS

3.1 Verification of Superposition Principle

Equations 13, 18 and 22 for two, three and four
group GPA are solved to estimate the displacements
generated. A parametric study is carried out to obtain
variations of the displacements and shear stresses with
depth, displacement ratio with spacing as functions of
L/d and the relative stiffness factor, K. The results are
presented for the following ranges of parameters: L/d: 5
to 50; K: 10 to 10,000, spacing S/d: 2 to 10 and \(v_s: 0.5\)
(undrained condition).

The interaction factors of two GPA group obtained
herein are compared with those from Poulos & Mattes
(1971). The loading in compressive piles is at the top,
while the pullout load is transferred to the tip of GPA.
The displacements in compressible pile and GPA are of
the same order if the contribution of stresses in
end-bearing in compression is small.

The interaction factors, \(\alpha_{GPA}\) of two group GPA for
L/d=10 & 25 with spacing as a function of relative
stiffness factor are presented and compared (Table 1)
and \(v_s\) values for floating piles in compression. The
ratios of interaction factors, \(\alpha_{GPA}\) for GPA and floating
pile are in good agreement for Ld = 10. The interaction
factors are comparable for compressible piles and GPA
with increasing spacing, S/d, and increasing relative
stiffness, K. For longer GPA, L/d=25, the ratio of
interaction factors for K=10 is 0.65. The ratios increase
with K and equal 1.0 for rigid pile (K=10,000).

The ratios of interaction factors for four GPA group
estimated by rigorous analysis and estimated by
superposition principle are presented in Table 2 and 3
as functions of K and L/d. The results are in good
agreement from the two approaches thus validating the
principle of superposition for interaction factors.

The variation of \(\alpha_{GPA}\) with spacing S/d as a function of
L/d are presented for two, three and four group GPA in
Figures 8 (a), (b) & (c) respectively for K=50 & \(v_s=0.5\).
\(\alpha_{GPA}\) decreases with L/d for all groups as is to be expected.
\(\alpha_{GPA}\) decreases from

| Table 1 Comparison of Interaction Factors of Two GPA in Pullout and of Floating Piles in Compression (Poulos & Mattes, 1971). |
|-----------------------------------------------|-----------------------------------------------|
| \(\alpha_{GPA}\) for L/d=10 & 25 | \(\alpha_{GPA}\) for L/d=25 |
| S/d=2 | 3 | 4 | 5 | S/d=2 | 3 | 4 | 5 |
| K=10 | 0.28 | 0.22 | 0.19 | 0.16 | 0.24 | 0.18 | 0.15 | 0.12 |
| 100 | 0.46 | 0.37 | 0.32 | 0.27 | 0.37 | 0.31 | 0.27 | 0.24 |
| 500 | 0.53 | 0.43 | 0.37 | 0.31 | 0.53 | 0.45 | 0.40 | 0.35 |
| 1000 | 0.54 | 0.44 | 0.38 | 0.32 | 0.58 | 0.49 | 0.44 | 0.39 |
| 10000 | 0.56 | 0.45 | 0.39 | 0.32 | 0.64 | 0.54 | 0.49 | 0.43 |
| \(\alpha_{GPA}\) for compression for L/d=10 | \(\alpha_{GPA}\) for compression for L/d=25 |
| K=10 | 0.29 | 0.22 | 0.18 | 0.15 | 0.37 | 0.28 | 0.22 | 0.18 |
| 100 | 0.45 | 0.36 | 0.31 | 0.26 | 0.41 | 0.35 | 0.3 | 0.27 |
| 500 | 0.53 | 0.43 | 0.36 | 0.31 | 0.53 | 0.45 | 0.41 | 0.37 |
| 1000 | 0.55 | 0.45 | 0.38 | 0.32 | 0.58 | 0.49 | 0.44 | 0.4 |
Table 2 Comparison of Interaction Factors of Group of Four GPA from Rigorous Method and Superposition for L/d=10

| S/d | 2  | 3  | 4  | 5  | 10 |
|-----|----|----|----|----|----|
| K=10| 0.78 | 0.60 | 0.50 | 0.43 | 0.25 |
| 100 | 1.29 | 1.03 | 0.86 | 0.74 | 0.41 |
| 500 | 1.49 | 1.19 | 1.00 | 0.85 | 0.46 |
| 1000 | 1.52 | 1.22 | 1.02 | 0.87 | 0.47 |
| 10000 | 1.56 | 1.25 | 1.04 | 0.89 | 0.48 |

α\text{IG2}, calculated/ α\text{IG2}, super-position

| K=10 | 1.01 | 1.01 | 1.03 | 1.02 | 1.04 |
| 100 | 1.01 | 1.01 | 1.03 | 1.02 | 1.05 |
| 500 | 1.01 | 1.02 | 1.03 | 1.02 | 1.05 |
| 1000 | 1.01 | 1.02 | 1.03 | 1.02 | 1.05 |
| 10000 | 1.02 | 1.02 | 1.03 | 1.02 | 1.05 |

Table 3 Comparison of Interaction Factors of Group of Four GPA from Rigorous Method and Superposition for K=50

| S/d | 2  | 3  | 4  | 5  | 10 |
|-----|----|----|----|----|----|
| L/d=5 | 1.17 | 0.88 | 0.69 | 0.56 | 0.27 |
| 10 | 1.14 | 0.90 | 0.76 | 0.65 | 0.36 |
| 25 | 0.88 | 0.71 | 0.61 | 0.53 | 0.34 |
| 50 | 0.76 | 0.61 | 0.51 | 0.44 | 0.28 |

α\text{IG2}, by super position principle

| L/d=5 | 1.18 | 0.89 | 0.72 | 0.58 | 0.28 |
| 10 | 1.15 | 0.92 | 0.78 | 0.66 | 0.37 |
| 25 | 0.90 | 0.73 | 0.63 | 0.54 | 0.35 |
| 50 | 0.80 | 0.63 | 0.53 | 0.46 | 0.28 |

α\text{IG2}, calculated/ α\text{IG2}, super-position

| L/d=5 | 1.01 | 1.01 | 1.04 | 1.03 | 1.01 |
| 10 | 1.01 | 1.01 | 1.03 | 1.02 | 1.01 |
| 25 | 1.02 | 1.02 | 1.03 | 1.02 | 1.00 |
| 50 | 1.05 | 1.04 | 1.05 | 1.03 | 1.01 |

Fig. 8 Interaction factor, α_1 vs. S/d for K=50 & vs=0.5 – Effect of L/d.

0.42 to 0.02, 0.83 to 0.04 and 1.17 to 0.05 with S/d increasing from 2 to 50 for L/d=5 for 2, 3 & 4 GPA groups. α_1 decreases from 0.42 to 0.28, 0.83 to 0.55 and 1.17 to 0.76 for L/d increasing from 5 to 50 for 2, 3 & 4 GPA groups. Variations of α_1 with spacing, S/d as a function of relative stiffness factor, K are presented in Figures 9 (a), (b) & (c) for two, three and four GPA groups respectively for L/d=10 and vs=0.5. α_1 considered for compressible GPA decreases from 0.27 to 0.02, 0.58 to 0.03 and 0.78 to 0.05 with S/d.
increasing from 2 to 50 respectively for 2, 3 & 4 groups of GPA. Variation of $\alpha_I$ with S/d for increasing K are similar to those for K=10 and become steep or slope increase for K increasing from 10 to 10000. $\alpha_I$ at S/d=2 increases from 0.27 to 0.55, 0.58 to 1.10 and 0.78 to 1.56 with K from 10 to 10000 for 2, 3 & 4 groups of GPA respectively.

4 CONCLUSIONS

Analyses of interactions in groups of 2, 3 and 4 GPA are presented in this paper. Group of 2 GPA is investigated for estimating the additional displacements due to the influence of load in the adjacent GPA. The interaction factors for group of 2 GPA are 3% & 30% less compared to the values for piles in compression (Poulos & Mattes, 1971) for L/d=10 & 25 respectively for K smaller than 500 while they are in close agreement with the values for piles for K>500.

The same approach is extended to estimate the additional displacements due to the loading in groups of 3 & 4 GPA. The interaction factors for two GPA group are validated with those of Poulos and Mattes (1971) for piles in compression. The interaction factors for 3 & 4 groups of GPA are estimated by superposition principle from the interaction factors of two GPA group. The results thus estimated from principle of superposition compare well with the results from the rigorous analysis.

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