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ORIGINAL ARTICLE

Numerical Modeling of Granular Anchor Pile System in Loose Sandy Soil Subjected to Uplift Loading

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Abstract During the last few decades various researchers have proposed appropriate experimental and numerical methods to estimate the uplift capacity of granular anchor piles (GAPs) in expansive soils. Surprisingly, very few studies have been performed to determine the uplift capacity of GAPs in loose sands. This paper presents the results of the numerical study to estimate the ultimate uplift capacity of group piles. Numerical analysis is performed using finite element software PLAXIS-3D. The foundation system is assumed to consist of a different number of regularly spaced GAPs installed in loose sandy soils. The analysis examines the influence of factors such as number of piles *n* and length *L* to width *D* ratio, and properties of the granular pile material and compares the efficiency of group of GAP systems of different configurations.

Keywords Granular anchor pile · Finite element method · Loose sand · Group piles · Uplift capacity

Notations

L	Length of a pile (m)
D	Diameter of a pile (m)
γ	Total unit weight of soil above the water table (kN/m^3)
γ_{sat}	Saturated unit weight of soil (kN/m^3)
ϕ	Angle of internal friction of soil (°)
c	Cohesion of soil (N/m^2)
v	Poisson's ratio
E_s	Elastic modulus of surrounding soil (kPa)
E_p	Elastic modulus of pile material (kPa)
E	Elastic modulus of plate element (kPa)
d	Thickness of a plate element (m)
S	Centre to centre spacing between piles in group piles (m)
n	Number of piles in a pile group
η	Efficiency

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Introduction

The construction of structures in the coastal areas consisting of weak soils at shallow depths requires due attention to be given on safety and stability of surrounding structures which may be under question due to poor engineering properties of weak soils. So, proper attention must be required in designing the foundation of structures in such conditions. Soil in these areas has to be improved using an efficient and economical ground improvement technique.

Ground improvement of loose cohesionless soils can be achieved by different methods such as excavation and replacement, compaction piles, compaction with explosives, vibro-flotation, well point system, dynamic compaction, grouting, etc. The selection of the most suitable method depends on different factors, including soil conditions, maximum depth of the compaction, required degree of the compaction, type of structures to be supported, etc.

On the other hand, ground improvement techniques are normally preferred for economical considerations. Out of several available techniques, granular piles have been widely used. Granular piles reinforce the surrounding soil and improve the engineering properties of the soil. It provides an effective drainage condition so that resistance offered to the liquefaction in loose saturated soils can be enhanced. This method also improves the stability of embankments, raise the consolidation rate, improve the bearing capacity of the soil, and reduce the settlements [1, 2]. Recently, the performance (behaviour) of stone columns is analyzed both experimentally and numerically by several researchers in soft soils with or without providing geosynthetics around the granular pile [3–5].

Recently there is marked increase in the construction of the transmission towers, high raised buildings and tall structures. The design of these engineering structures requires that the foundation system should also resist vertical uplift forces. In such situations, the granular pile alone cannot help much in the case of tensile/uplift force, and hence an attractive and economical design solution may be required. It can be achieved with the slight modification in granular pile. A base plate is provided at the bottom of pile and it is connected with an anchor rod to resist the uplift forces coming to the foundation. The concept of having compressible piles to resist the uplift loads is relatively new, economical and efficient ground improvement technique [6] and it is known as granular anchor pile (GAP) system.

GAP system is suitable for soft soils or weak soils. When the loose sandy soils are required to withstand compressive loads as well as tensile loads coming to the foundation, the GAP system provides an economical and safe solution. These piles are ideally suitable for expansive soils too.

A well-documented study on the GAP system has been carried out in the laboratory and field study before its application to actual field conditions [6–10]. The parametric analysis was performed to determine the ultimate pullout capacity of GAP in homogenous and non-homogenous soft ground [11, 12]. A small-scale numerical analysis was performed on GAP in expansive soils [13, 14]. A very few field studies have been performed on GAP system in loose cohesionless soils in literature [1, 15]. Kranthikumar et al. [16] analyzed GAP system in loose cohesionless soils using Plaxis-3D and presented a detailed parametric study for single pile system.

A critical review of the literature pointed out very limited attempts [13, 14] towards the numerical modeling of GAP system in expansive soils. However, no numerical study seems to be available to analyze the performance of a group of GAPs in loose sandy soils subjected to the uplift loading. In this study, the performance of a group of GAPs under uplift loading condition is examined by using three-dimensional finite element analysis with PLAXIS 3D software. An attempt is made to investigate the influence of factors such as number of piles n, spacing of piles S, and soil–pile properties on the uplift capacity of GAP system. The group efficiency of the GAP system in loose sandy soils under uplift loading is also determined.

Numerical Modelling of Gap System

A prototype model of GAP system with different length to diameter ratios has been numerically modelled for the analysis using finite element software PLAXIS 3D. Figure 1 shows the concept of GAP system. A loose sand soil bed was considered around the granular pile. Soil layer was assumed with suitable plan dimensions and depth and was modelled for the analysis using the borehole option in PLAXIS. The modelling of a single granular pile was done by using poly-curve and extrudes options. Group piles was modelled using create array option. The arrangement of piles in a pile group is shown in Fig. 2. The footing and anchor plate were modelled as the plate element and the node-to-node element was used to model the anchor rod of GAP system. Modeling of group piles is done by using array option in structural mode. The volume elements were modelled as ten-node tetrahedral elements. The plate elements were modelled using six-noded triangular elements. These elements assume linear variations in strains and stresses with respect to coordinate axes. The diameter of the anchor plate was same as the diameter of granular pile. A linear elastic model was considered for plate elements with node-to-node anchor. A drained condition was used for both soil and pile. Mohr–Coulomb (MC) failure criterion was used for defining the constitutive relationship of volume elements like granular pile and loose sandy soil. For both pile and soil, a constant soil modulus throughout the depth was assumed.

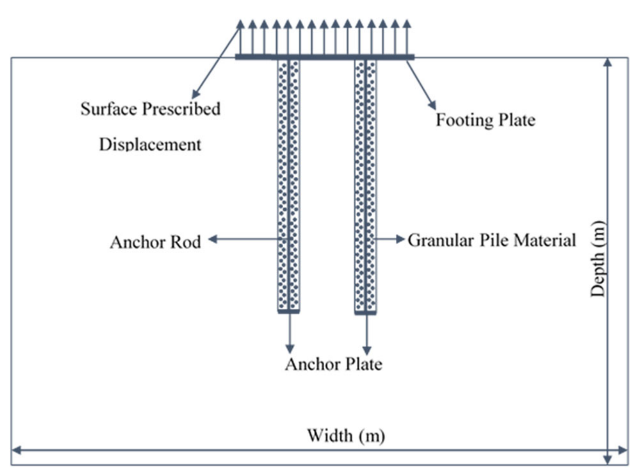

Fig. 1 Modeling of granular anchor pile system

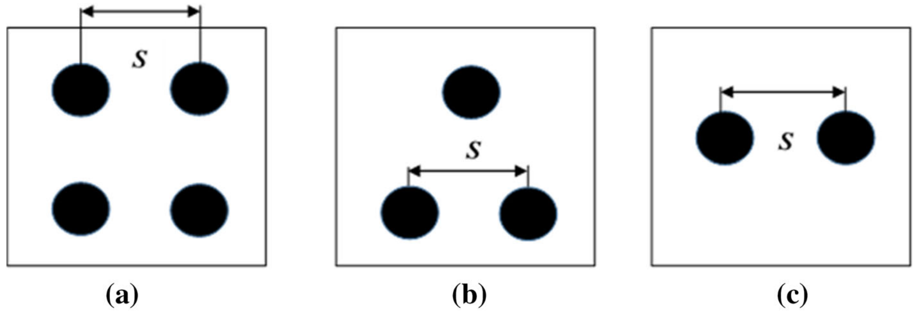

Fig. 2 GAP group configuration for **a** 4 piles (square pattern), **b** 3 piles (equilateral triangle pattern) and **c** 2 piles

The boundary conditions of the GAP model were assumed as standard fixity conditions. Roller conditions were assumed on the vertical boundary surfaces, whereas full fixed condition at the base of the geometry. Similarly all boundary surfaces are permeable. In finite element method, mesh generation plays a crucial role for calculation of accurate values, so a simple fine global finite element mesh was used for the analysis to get more precise values. Figure 3a shows the meshing of GAP system for a group of 4 piles. Nodal points were selected at the centre of each granular pile to find out the uplift capacity of the GAP system. An upward prescribed displacement of 10 % diameter of pile was given on the top footing. Although GAP system may withstand more load and undergo higher vertical displacement, a unique value of upward displacement (10 % diameter) is selected to compare all configurations. Figure 3b shows the bulging of GAP system after the application of given prescribed displacement.

Validation

The accuracy of the proposed numerical modeling in PLAXIS 3D was validated by comparing the field results of GAP system performed on cohesionless soils [1]. The size of the soil test bed assumed in the analysis was 5 m × 5 m × 5 m. The dry unit weights of the granular pile and cohesionless soil were 22 and 17 kN/m^3, respectively [1]. The pile and soil modulus were 12.3 and 4.3 MPa respectively [1]. The diameter of anchor plate was same as the diameter of the pile and thickness was 0.0254 m. The length of anchor rod was same as the length of pile with diameter 0.016 m. For both anchor rod and anchor plate, the mild steel material with a high flexural rigidity was used for avoiding buckling and deformations.

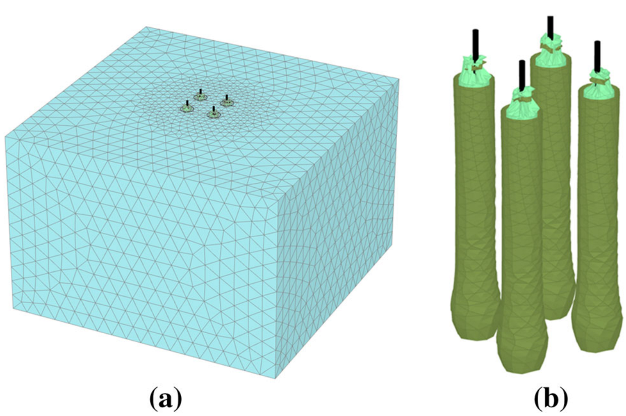

Fig. 3 **a** Meshing of GAP system, **b** 4 piles with interfaces and anchor rods

Figure 4 shows the uplift curves of numerical analyses and field test for GAP system in loose cohesionless soil. The uplift force curves of numerical analyses and field test follow the similar trend. The uplift capacity obtained from the field test and the numerical analyses were 50 and 47.2 kN, respectively, for 3.5 m length pile. The variation in uplift capacity is due to the process of construction and overburden on the soil due to the heavy weight of the equipment.

Parametric Study

A horizontal soil layer of 10 m thickness was modeled with the borehole option in PLAXIS 3D. The modeling of GAP system was introduced in structure mode. Loose sandy soil

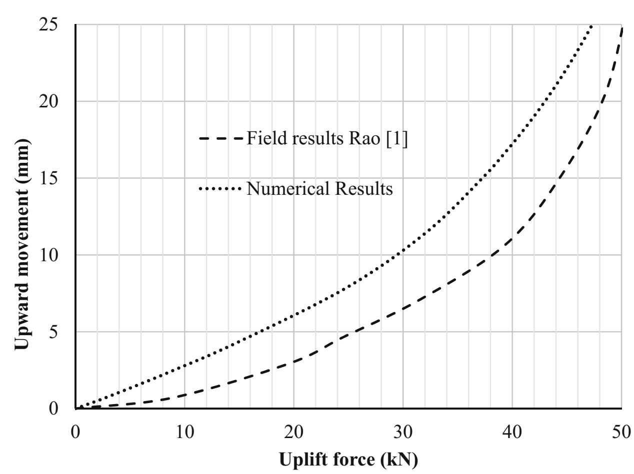

Fig. 4 Uplift force curves of numerical and field results

was modeled using ten-noded tetrahedral elements. Granular pile was also modeled in continuation of loose soil, with different properties. Base plate and footing were modeled using six-noded elements. Loose sand was assumed as completely dry soil. The diameter of granular pile was 0.5 m and length to diameter ratio (*L*/*D*) of pile was varied from 5 to 15. Footing of GAP system was not fixed and its dimension was taken as 10 mm projection from the edge of granular pile. For avoiding buckling and deformation, a higher value of flexural rigidity was assumed for anchor rod, anchor plate and footing. The input model parameters of the soil and granular pile are given in Table 1 [1] whereas the material properties of the structural elements are reported in Table 2 [1]. The response in the form of uplift force-upward movement relationship was obtained for the various configurations considered in the parametric study.

Analysis of a Single Pile

Interface between two different materials has a critical role in numerical modeling. In Plaxis-3D, it is accounted by providing suitable values of the strength reduction factor R_{inter} for interfaces. Values of normal stiffness and shear stiffness of interface element are directly proportional to R_{inter} hence mobilized shear resistance along interface can be modelled by adjusting the value of parameter. It depends on roughness of pile/plate material and nature of contact developed with soil in contact. The effect of the strength reduction factor (R_{inter}) for interfaces on the uplift capacity of the GAP system are summarized in Table 3 ($D = 0.5$ m, $L/D = 10$). With reduction in the R_{inter} for interface between pile and soil, the uplift capacity decreases. However, there is no significant effect of R_{inter} for interface between pile and plate on the uplift capacity.

Uplift capacity of the GAP system of single piles for different *L*/*D* ratios is summarized in Table 4. The uplift capacity increases with an increase in the *L*/*D* ratio of a pile for a given diameter. The uplift capacity of GAP system increases by 30 % when *L*/*D* ratio increases from 5 to 7.5. Further increase in *L*/*D* ratio from 7.5 to 10, 10 to 12.5 and 12.5 to 15 resulted 20, 15 and 15 % increase, respectively. This shows that the uplift capacity of a pile improves significantly with an increase in length of a pile up to a significant length after which the increase in the length does not contribute much towards the load sharing. From the analysis, it can be observed that the optimum length is about 10 times the diameter of the pile.

Table 2 Material properties of plate elements used in the numerical model

Model type	Parameters	*d* (m)	*E* (GPa)	*v*
Linear elastic	Anchor plate	0.025	200	0.15
	Footing	0.01	200	0.15

Effect of Group Piles

Numerical analysis was performed on group of GAPs with *L*/*D* ratio ranging from 5 to 15 for a pile diameter, 0.5 m with constant spacing (3*D*). Figure 5 shows the response of group piles and a single pile in loose sand under uplift loading. To facilitate comparisons between group piles and a single pile, the uplift force per pile in a group was calculated by dividing the uplift force of a pile group by the number of piles in the group. The curves of load per pile in pile group and a single pile are similar in shape. The upward movement in the pile group is observed to be increasing with the number of piles in the group due to interaction effects between the piles. If a pile group moves upward, the pressure bulb for the individual piles in the group overlaps, and thus reduces the uplift load carried by the each pile in the pile group.

The efficiency of a pile group of a GAP system for a given upward movement is calculated as follows:

$$\text{Efficiency}\,(\eta) = \frac{\text{Uplift capacity of a pile group}}{(\text{Number of piles}) \times (\text{Uplift capacity of a single pile})} \quad (1)$$

Uplift capacity of the GAP system of different pile-group configurations for different *L*/*D* ratios is summarized in Table 4 along-with efficiency in each case. It is observed that group efficiency of a GAP system decreases with increase in the number of piles in a given pile group on the account of interaction effects. As number of piles in the group increases, the load carrying capacity of the group piles may reduce due to the overlapping of the stresses transmitting in the piles to the surrounding soil. For upward

Table 1 Material properties of soil elements used in the numerical model

Parameters	γ (kN/m^3)	γ_{sat} (kN/m^3)	*c* (kN/m^2)	ϕ (°)	*E* (MPa)	*v*
Loose sand	17	19	0	29	3800	0.3
Pile material	22	24	0	36	15,000	0.3

Table 3 Uplift capacity of a GAP system for different R_{inter} values of soil and pile ($D = 0.5$ m, $L/D = 10$)

R_{inter} of pile-plate	Uplift capacity (kN) of a single pile for R_{inter} values of pile-soil				
	1.00	0.95	0.90	0.85	0.80
1.00	112.534	110.361	107.971	105.379	102.643
0.95	112.474	110.304	107.931	105.329	102.595
0.90	112.390	110.236	107.867	105.274	102.539
0.85	112.304	110.155	107.791	105.202	102.472
0.80	112.213	110.058	107.699	105.317	102.391

Table 4 Uplift capacity and efficiency of a GAP system for a given diameter $D = 0.5$ m

Diameter (m)	Length (m)	L/D	Upilft capacity (kN)				Efficiency (%)		
			1 pile	2 piles	3 piles	4 piles	2 piles	3 piles	4 piles
0.5	2.50	5.0	62.49	119.32	174.25	230.72	95.47	92.94	92.30
0.5	3.75	7.5	92.59	181.65	265.96	350.19	98.09	95.75	94.56
0.5	5.00	10.0	112.53	221.55	326.48	431.59	98.44	96.71	95.88
0.5	6.25	12.5	128.70	254.36	375.36	497.17	98.81	97.22	96.57
0.5	7.50	15.0	144.08	284.68	420.59	557.80	98.79	97.30	96.79

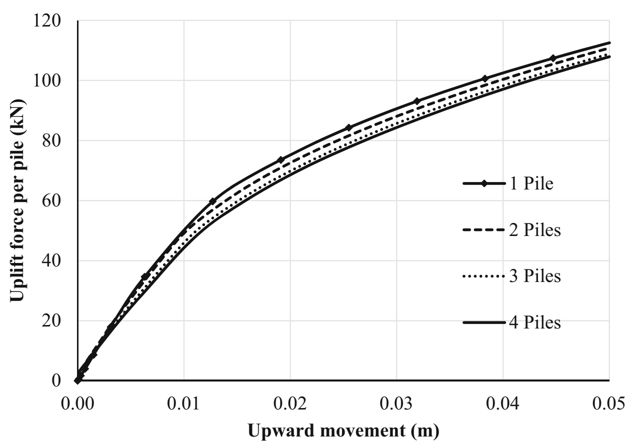

Fig. 5 Uplift force per number of piles of a GAP system ($D = 0.5$ m and $L = 5$ m)

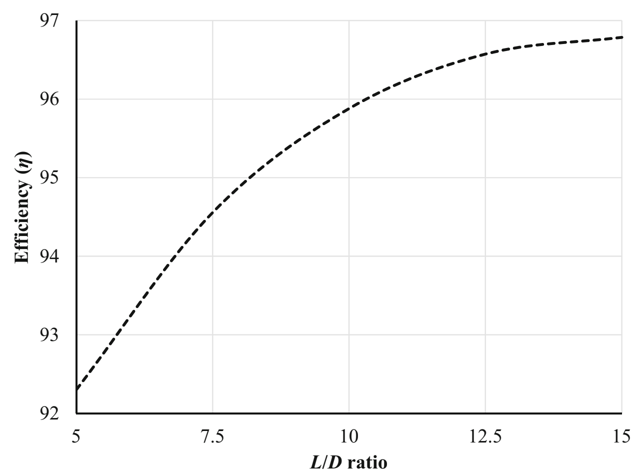

Fig. 6 Efficiency versus L/D ratio of GAP system for a pile group (4 piles, 3D spacing and $D = 0.5$ m)

movement of 0.1D, the group efficiency of GAP system ranges from 0.9 to 1.0 for a given spacing.

Figure 6 shows the variation of the efficiency of a GAP system with L/D ratios ($D = 0.5$ m, $n = 4$) of a pile group for a particular spacing (3D) between the piles. The efficiency of GAP system for a group of 4 piles increases with increase in the L/D ratio of a pile. The efficiency of pile group increases with in L/D ratio up to 10–12.5 after that the efficiency approaches constant value with L/D ratio.

Effect of different pattern of GAP system was examined ($D = 0.5$ m, $L/D = 5$, 10) and efficiency is summarized in Table 5. Only marginal change in the efficiency of GAP system is observed indicating negligible influence of the arrangement of piles in a pile group.

Effect of Depth of Water Table

Figure 7 shows the effect of depth of water table on uplift capacity of GAP system for four different lengths ($D = 0.4$ m and $L = 3$–6 m). Uplift capacity of GAP system decreases with increase in the depth of water table from the ground surface on the account of reduction in the effective stress and shear strength of soil. With increase in the depth of water table, the uplift capacity increases by 7–8 % for every metre up to 4 m from top of the ground surface for a pile of length 6 m after that uplift capacity increases by less than 6 % for remaining 2 m. The variation may be due to the bulging at the bottom of

Table 5 Effect of arrangement of piles in a group on the efficiency of GAP system

Diameter (m)	Length (m)	L/D	Efficiency (%)			
			3 piles		4 piles	
			Line pattern	Triangle	Line pattern	Square
0.5	2.5	5	93.04	92.94	91.56	92.30
0.5	5.0	10	96.87	96.71	96.01	95.88

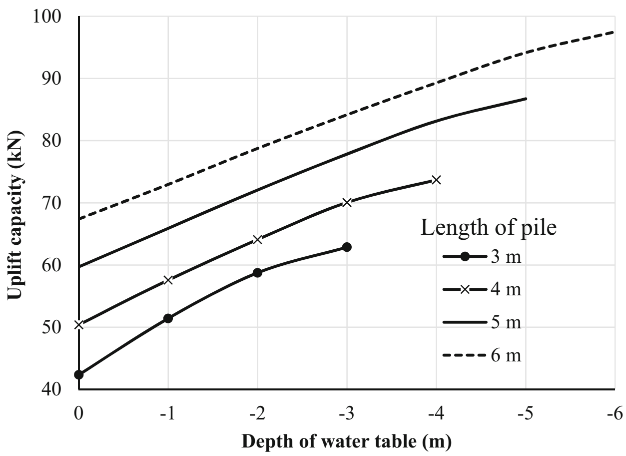

Fig. 7 Effect of water table depth on uplift capacity of GAP system ($D = 0.4$ m)

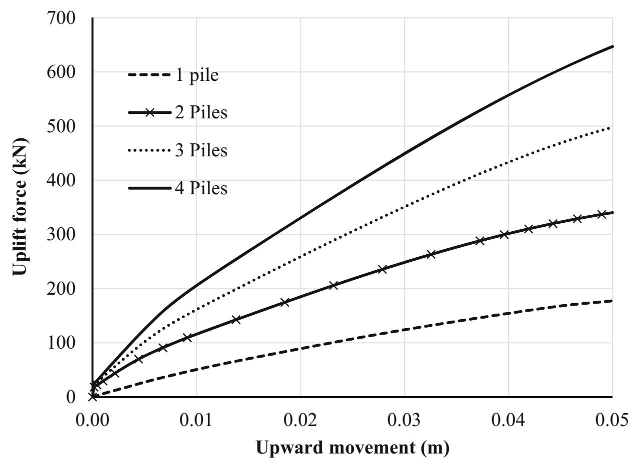

Fig. 8 Uplift force versus upward movement curves for different number of piles by considering construction effects

granular pile. Variation in the ultimate capacity is almost linear with the depth of water table.

Effect of GAP Construction

The uplift capacity of a GAP system mainly depends on soil and pile properties and also depends on the degree of compaction used for the granular pile. During the compaction of granular pile, the surrounding loose soil also undergoes compaction. So the shear strength properties of the loose soil around the granular pile get modified. The change in the state of strength while installing the GAP into the soil can be estimated by cylindrical cavity expansion theory (CCET) as proposed by Randolph et al. [17]. Randolph et al. [17] have revealed from the numerical study that expanding a cavity by doubling the radius is adequate to simulate expansion of cavity from a zero initial diameter. McCabe et al. [18] have concluded that if a lateral strain of 10 % is applied to the granular pile in PLAXIS 3D then the radial stresses generated in the surrounding soil closely follow the CCET formulation developed by Gibson and Anderson [19].

A similar methodology is adopted in the present study to analyze the effects of compaction during installation process. Lateral strain of 10 % was applied at calculation stage to consider the compaction effects of granular pile. Numerical model was developed to know the variation of uplift capacity and efficiency of GAP system with the effects of the construction. Figure 8 shows the uplift capacity curves of a GAP system considering the effects of compaction during the installation of granular pile ($D = 0.5$ m and $L/D = 10$). Uplift capacity is more for GAP system with construction effects compared to the GAP system without considering construction effects. The uplift capacity is higher due to densification of the surrounding loose soil during the construction of granular pile. Table 6 summarizes the results of three cases for highlighting the effects of the construction ($D = 0.5$ m no lateral strain, $D = 0.5$ m 10 % lateral strain and $D = 0.45$ m 10 % lateral strain). Uplift capacities for GAP systems with 10 % lateral strain for both diameters (0.45 and 0.5 m) are higher than those with no lateral strain with 0.5 m diameter. From Table 6, it is observed that the efficiency of pile group decreases considering the effect of compaction by lateral strain compared to the GAP system without considering construction effects.

Conclusions

A parametric study has been performed using 3-D finite element software PLAXIS 3D to study the performance of a GAP system in a loose sandy soil. The effects of key

Table 6 Uplift capacity and efficiency of a GAP system considering effects of construction

Diameter (m)	Length (m)	1 pile	Uplift capacity (kN)		Efficiency (%)		Lateral strain
			2 piles	4 piles	2 piles	4 piles	
0.5	5	112.534	221.548	431.588	98.436	97.403	0
0.5	5	177.490	340.219	646.786	95.842	95.054	10 %
0.45	5	155.635	290.211	564.529	93.234	97.262	10 %

parameters such as *L*/*D* ratio, number of piles and compaction effects on the uplift capacity of a GAP were examined. Based on the present study, the following conclusions can be made:

- The uplift resistance of the GAP system in a loose sandy soil increases with increase in the length and diameter of the pile.
- The uplift capacity of GAP system increases around more than 25 % when *L*/*D* ratio increases from 5 to 7.5 and 7.5 to 10. However further increment in *L*/*D* ratio from 10 to 12.5 and 12.5 to 15 results marginal increase (15 %) in the uplift capacity.
- The efficiency of pile group decreases with increase in the number of piles for constant spacing, because if number of piles in a group increases, the load carrying capacity of pile group may reduce due to the overlapping of the stresses transmitting in the piles to the surrounding soil.
- The uplift capacity of GAP system is observed to be higher by considering the effects of construction due to densification of the surrounding soil.
- Efficiency of group piles of GAP system lies between 0.9 and 1.0 for different number of piles with different diameters and *L*/*D* ratios.
- The variation of uplift capacity of a GAP system with depth of water table is almost linear. The uplift capacity decreases with increasing the depth of water table.

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