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Numerical Analysis of Inclined Granular Pile Anchor Subjected to Uplift Forces in Expansive Soil using Abaqus

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Abstract

Granular pile anchor is a new technique that is commonly used to improve the pull-out resistance of expansive soil like soft clay, loose sand, and black cotton soil. Using the Abaqus software, this work presents a numerical investigation to estimate the pull-out capacity of granular pile anchor in soft clay. By applying a specified displacement of 10% of D (pile diameter) on the granular pile anchor, the effects of length, diameter, angle of inclination (α), and number of GPA at varying spacing values on uplift capacity is examined. Additionally, L/D ratios of both individual and group piles are examined using various variables. The study uses expansive soil and GPA of unit weight 17 kN/m3 and 22 kN/m3, poisson's ratio of 0.4 and 0.3, modulus of elasticity 4 MPa, and 11 MPa, respectively, for the estimation of uplift capacity. The cohesion value for the expansive clay is 25 kPa, and the angle of shearing resistance for GPA is 36˚. According to the numerical study, both for a single pile and for piles placed in a group, with increases in pile length and diameter, the granular pile anchor's pull-out capability improves. For a pile placed in group the value of the pull-out capacity shows optimum result when spacing (S) is 2.5D. Additionally, the uplift capacity of the granular pile anchor increases with an increase in angle inclination (α) from 0˚ to 10˚, and then decreases from 10˚ to 15˚. The efficiency of GPA is examined, which assists in the choice of the different granular pile anchor parameters.

1. Introduction

The majority of middle part and south India is covered up with the expansive soil strata. After water absorption, expansive soils are prone to alternate shrinkage and swelling [1-2]. Because of their tendency to expand or contract whether wet or dry, expansive soils present a variety of difficulties. Lightweight structures built over expansive soils such as small office buildings, highways, airstrips, and other major structures, are highly affected by fluctuations in the water content. These soils primarily contain the mineral montmorillonite that has a strong affinity for water and causes swelling and shrinking as a result of changes in moisture levels. The main structural part of the mineral montmorillonite is an octahedral film of alumina in the middle, which is sandwiched between two tetrahedral layers of silica, and has a thickness of about 10 Å. Due to the lack of available land for infrastructure projects, several approaches are currently being used to treat poor soils so that stable, long-lasting foundations may be built over them. Physical modification, chemical modification, and tension-resistant footing are some of the several foundation approaches that are being used to decrease the swell-shrink behaviour of poor soils in response to fluctuations in water conditions. Sand cushions [3-5] and the cohesive non-swelling (CNS) layer [6] are components of the physical modification technique. Mixing chemicals like lime, fly ash, Portland cement, $CaCl_2$ and construction and demolition waste is a part of the chemical modification technique [7-14]. Underreamed piles [15, 16], belled piers and drilled piers [2], as well as deep foundation [17, 18], are all parts of the tension-resistant system. The methods mentioned above, however, have significant drawbacks [15, 19] since some of them take a lot of time, need trained labour, and have

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expensive installation procedures [20]. Granular pile assembly has been found to be an extremely effective and efficient method for increasing the pull-out capacity and decreasing the settlement of soft clays, loose sands, and expansive soils [21, 22]. Using granular pile anchors increases the load bearing capacity, reduces settlement, and stabilises embankments constructed on unstable soil. Granular piles have been claimed to increase the geotechnical characteristics of expansive soil beds and loose sands [21, 23, 24]. A study of geotextile granular fill in soft soils with granular piles found that the settlement value could be decreased [25, 26]. The improvement in the increase of soil consolidation with the use of granular pile is explored by developing a mathematical model and accounting for the effect of blockage due to particle migration [27]. By making a minor adjustment to the typical granular piles, a new compression pile model that can also resist tensile pressures has been created [28]. A new technique named as granular pile anchor is frequently used to improve the uplift resistance of poor expansive soils such as loose sands, soft clays, and black cotton clays. In cohesive and sandy soils, a conventional shallow foundation may not be capable of withstanding the significant uplift forces; in such situations, pile foundations such as concrete pile, under reamed pile, and belled pier foundations are recommended. Deep foundations have been used to support a variety of construction types for ages. They are especially useful when the soil's shallow depths don't have a sufficient load-bearing capacity to support the anticipated loads of buildings. Granular piles are widely known and supported by studies for their ability to increase the carrying capacity of weak soils and reduce settlement rates but little is known about how effectively they can resist uplift. A granular pile cannot withstand uplift forces on its own because the discrete particles of a granular pile are not interconnected, it cannot resist uplift forces caused by swelling of soils and severe wind loads. Previous studies have shown that granular piles can assist in improving a soil's bearing capacity and decreasing settlements in poor soils [29, 30]. These piles are installed using a procedure that compacts the actual soil deposits into a composites mass, improving shear strength and load displacement behaviour [22, 29, 30]. The effectiveness of granular piles is decreased by their tendency of bulging at the upper end of pile. The effectiveness of granular piles has been improved by the use of granular anchor pile foundations, which are built with an anchor plate at the bottom of the granular pile and a steel rod connected to the base of foundation. With the use of a mild steel tendon, an anchor plate is anchored at the base of the granular pile in this design [31-34]. This allows the anchor system to behave as a single unit and also provide tension resistance. Due to the downward pressure of the weight of the granular pile, uplift resistance forms at the pile-soil interface, and the uplift force on the foundation is further increased by the accumulation of friction along the cylindrical pile-soil interface. The anchor's impact causes the GAP to become tension resistant, and the uplift force operating on the footing is to be restricted. The friction formed at the pile-soil interface can counteract the upward force acting on the foundation since the weight of the anchor sheet and the downward force of granular material limits the upward force acting on the foundation. Before installing the GPA mechanism in actual field settings, a small-scale laboratory model is created, and a simple approach for constructing and installing granular pile anchor (GPA) in soft clay is given [31]. With the application of the GPA system, it has been discovered that the rate of heave is reduced [28, 33]. According to field experiments done by various researchers, the pull-out resistance of the poor residual soils reinforced by granular pile anchor GPA and conventional concrete piles improved with the application of GPA compared to that of standard concrete piles in both moist and dry conditions [32, 33]. When applied to cohesionless soils, the pull-out capacity of GPA showed an improvement in the uplift capacity up to an L/D ratio of 10, so selecting L/D = 10 as the optimal number, while with fixed values of spacing, the effectiveness of the GPA group decreased with more piles because the pressure bulb around the pile shape overlapped [20, 29]. Various studies of numerical analyses of GPA on poor soils show good uplift resistance [35-37]. Increasing the numbers of geogrids resulted in an improvement in the uplift capacity due to their effect on expansive soil uplift resistance [38-40].

The literature studies mentioned above demonstrate the GPA's resistance to uplift forces in sand and clay utilising experimental and computational approaches. The use of GPA in expansive soil increases the pull-out capacity of the anchor as compared to a simple anchor embedded the soil. The expansive soil contains the clay mineral montmorillonite, which expands when comes in contact with the moisture. Due to the expansion of the soil, it induces radial stresses on the GPA which increases the resistance of the anchor to the uplift forces. This work aims to find out the pull-out capacity of the inclined GPA in expansive soil using numerical analysis in Abaqus 2017 by varying parameters as: length of the anchor, spacing between the group of anchor pile, diameter of pile anchor, and inclination of the anchor with respect to vertical. The effects of various GPA variables have been evaluated for a specified displacement of 10% of pile diameter [20, 29]. The effectiveness of the pile group has also been evaluated in the current analysis since it is a major factor in choosing the pile parameters.

2. Problem Domain and Parameters Varied

Using the finite element (FE) programme Abaqus, a numerical investigation of the uplift capability of granular pile anchors has now been conducted. The software used for numerical stability analysis is Abaqus 2017 with a standard explicit model. Geometry type is deformable for expansive soil and discrete rigid for GPA and geometry shape is solid for both expansive soil and GPA. For the structure of the numerical model, all of the sections are made in the part module. Then all of the sections are given material properties in the property module. Finally, all of the sections are assembled in the assemble module. After that, boundary conditions, loading, and meshing are set up to run the analysis. For the investigation of uplift capability, a granular pile anchor model with various lengths and diameters is modelled. Numerical studies have been done to determine how important parameters like the diameter, length, and distance between two granular pile anchors effect uplift capacity. This model is embedded in the expansive clay having dimensions length is 10 m, width is 10 m, and depth is 20 m, as shown in Figure 1. The model 10m x 10m x 20m was used in the present study. The lateral boundaries of the tank were selected such that pressure bulb does not the intersect the boundaries of the tank. The maximum pressure bulb was extended up to 2.5D to 3D in the lateral direction. Hence, the dimensions of the tank used in this study are greater than 2.5D to 3D in lateral direction. For calculating the pull-out capacity in this study, the pressure bulb in the vertical direction is in upward direction, so the depth of the tank is taken more than the maximum length of the pile.

The diameter of each GPA is decided on the basis of the corresponding fixed L/D ratios for each length of the GPA. Various factors such as the pile anchor length, diameter, inclination of anchor pile, and spacing of pile anchor were taken into consideration for the numerical modelling. Table 1 provides the different parameters used and varied. The Abaqus software has been used to provide a model scale analysis; it will help the geotechnical engineers select suitable design criteria for installing granular pile anchor in the ground.

Table 1. Different parameters used in numerical modelling.

Length of GPA (L) (m)	Inclination of GPA (α) (degree)	Diameter of GPA and anchor plate (D) (m)	Thickness of anchor plate (mm)	Spacing of pile (S, m)	L/D ratio
4	0, 5, 10, 15	0.2, 0.3, 0.4, 0.6, 0.8, 1.2	25	2D,2.5D,3D	20, 13.33, 10, 6.67, 5, 3.33
8	0, 5, 10, 15	0.4, 0.6, 0.8, 1.2, 1.6, 2.4	25	2D,2.5D,3D	20, 13.33, 10, 6.67, 5, 3.33
12	0, 5, 10, 15	0.6, 0.9, 1.2, 1.8, 2.4	25	2D,2.5D,3D	20, 13.33, 10, 6.67, 5

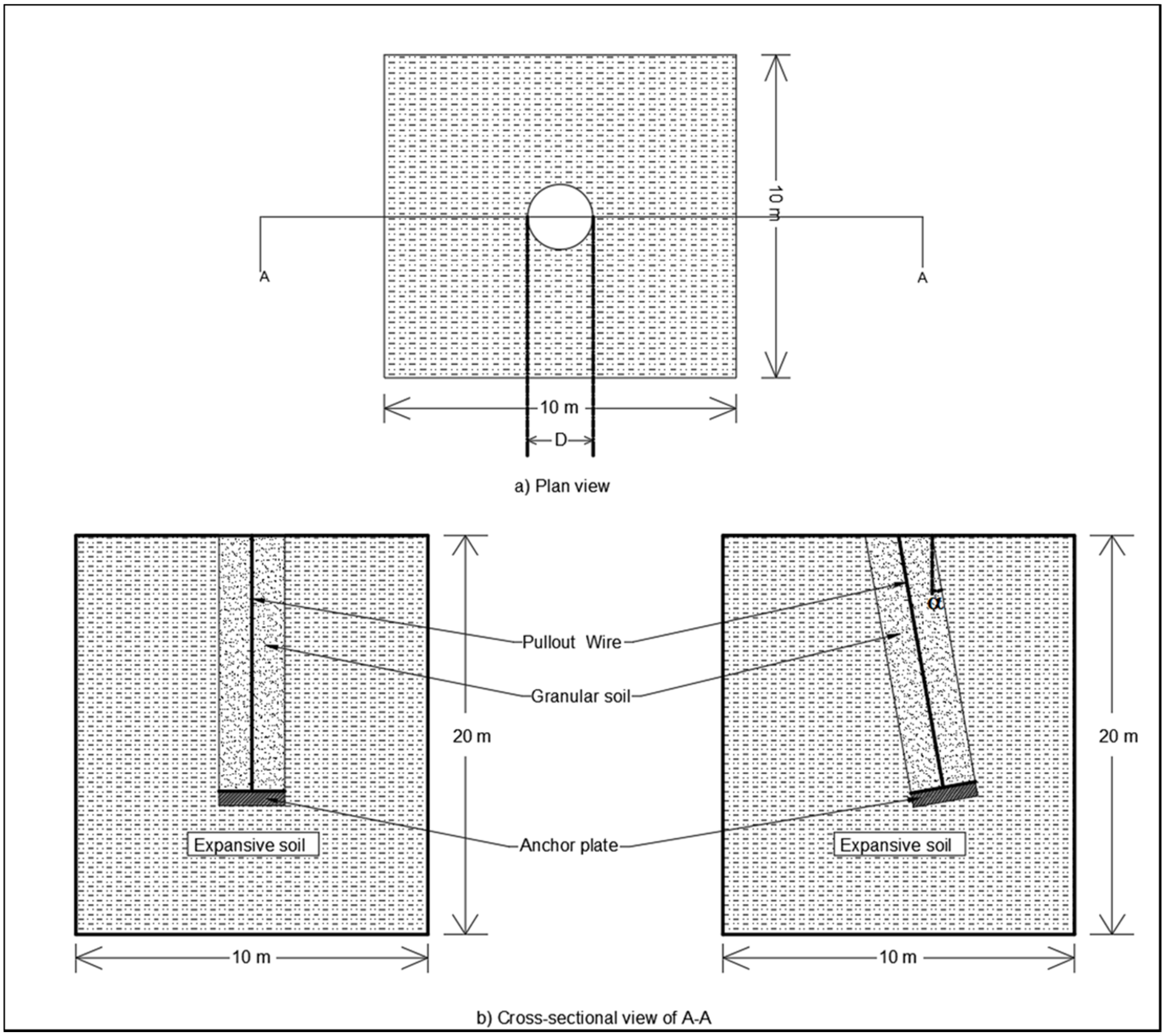


Figure 1. (a) Plan view of granular pile anchor embedded in Expansive soil (b) Cross-sectional view of A-A of expansive soil and GPA with angle of inclination.

3. Modelling Parameters and Mesh Convergence Study

The soil model is made of expansive soil and granular pile anchor. GPA is made up of a granular soil. Granular anchor pile was constructed using an anchor wire fastened to the foundation's base and an anchor plate at the granular pile's base. The assumption made in the analysis is that the uplift capacity is unaffected by the water table. The properties of expansive soil like, unit weight, cohesion, poisons ratio, elastic modulus, and properties of GPA like unit weight, friction angle, poisons ratio, elastic modulus are given in Table 2 [34]. The Mohr-Coulomb model is used for simulation techniques. This model uses the shear strength parameters (cohesion and friction angle) of the soil to calculate the shear resistance along the pile-soil interface. The pull-out capacity can be estimated using the equation:

$Fp = \int \tau p \, dx$

where Fp is the uplift force, τp is the shear stress along the pile-soil interface, and dx is the displacement of the pile.

The boundary condition used for analysis is of displacement/rotation type. To perform finite element analysis in Abaqus, all four of the soil's side faces are subjected to the boundary condition in order to constrain their horizontal movement and the bottom of the soil model is restricted for all the movements. Using the Mohr-Coulomb criterion, the relation in between granular pile and clay is established. The Mohr-Coulomb model not only involves less computation time for the analysis than any other soil hardening model but also requires less parameters for the simulation of the model, hence it is adopted for the present study [41]. Interaction characteristics between the expansive soil and the GPA were provided by the interface rigid surface (IRS) contact element [41]. It is important to know that the IRS interface element keeps the two materials from mixing. The interaction property manager for the selected surfaces calculated the tangential friction angle between expansive clay and GPA using penalty technique and a coefficient of friction of 0.4. Using the hit and trial approach on various diameter values, the group effects of piles is taken into account to prevent the impact of border constraints, and the influence of boundary conditions was found to be minimal when the footing diameter was kept at four times the pile diameter. Three different spacing values 2D, 2.5D, and 3D were used to evaluate group effects of GPA. The results of the GPA system's uplift behaviour are graphically represented, with displacement (m) on the x-axis and the associated uplift force (kN) on the y-axis. In each model, related uplift is calculated by applying an upward displacement of 10% D on the GPA [20, 29]. Meshing was designed in such a manner that it was finer near the footing (i.e. at the centre) and coarse away from the footing. C3D8R element was used for the meshing; Figures 2, 3(a), 3(b), and 4 depict the boundary condition, loading, assembly, and meshing. According to the mesh convergence study, 25760 was the optimized number of elements for this study. Therefore, 25760 elements were used in this study. Beyond this range, the pull-out capacity of the model did not significantly alter (1.3%).

Table 2. Properties of soil, GPA, and structural element.

Material property	Clayey soil	GPA	Anchor plate
γ (kN/m^2)	17	22	-
Cohesion c (kPa)	25	0	-
Angle of shearing resistance (ϕ, degree)	0	36	-
Poisson ratio (υ)	0.4	0.3	0.15
Modulus of elasticity E (MPa)	4	11	2×105

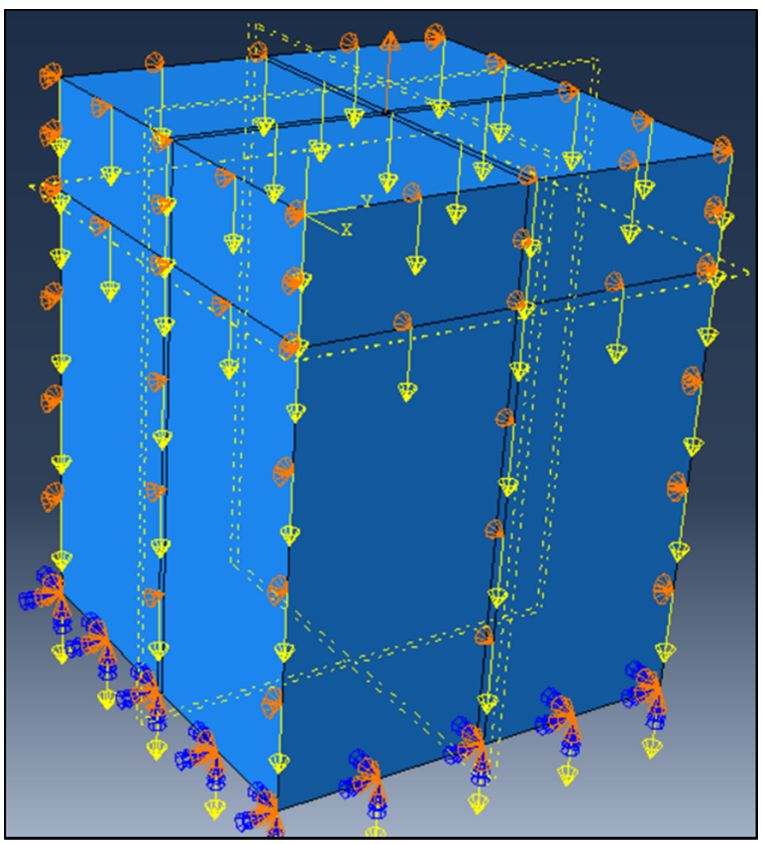
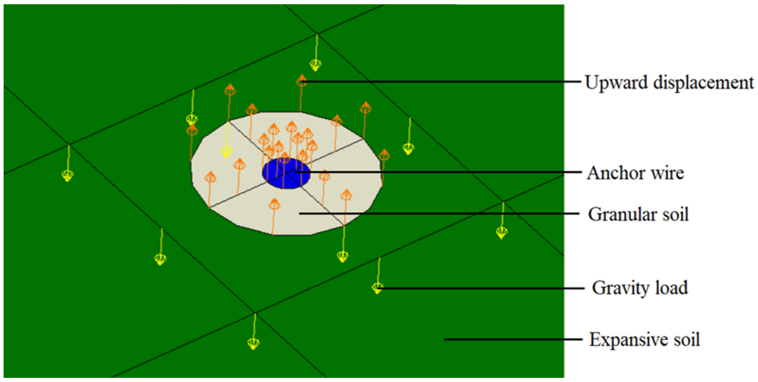


Figure 2. Boundary constraints added for generating actual field condition.



(a)

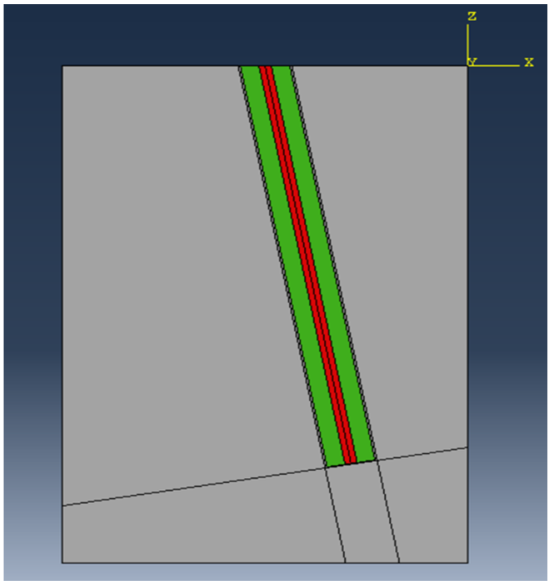


Figure 3. a). Load applied in the form of specified displacement to the single GPA. b). Assembly of 10° inclined GPA embedded in expansive soil.

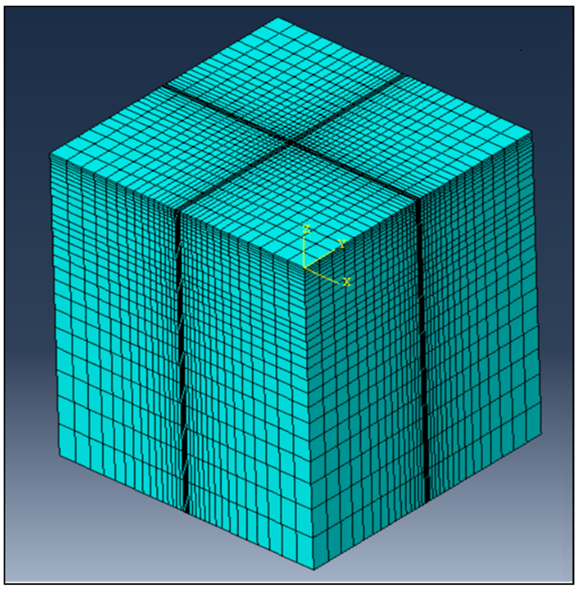


Figure 4. Meshing of the numerical model.

4. Software Validation

An additional investigation was performed to validate the software, and the findings were compared with those reported in [40]. For the purpose of numerical analysis, the values of sand like maximum dry density is 15.99 kN/m^3, cohesion is 0.036kg/cm^2, poisson's ratio is 0.45, elastic modulus is 51.6 MPa [42,43], interface frictional angle is 37.8° corresponding to 45% relative density. The unit weight of pull-out wire is reported to be 78 kN/m^3 and elastic modulus is 2.2 * 10^5 MPa. All the above values are considered for software validation. The experimental study was conducted in a test tank of size 700 mm × 450 mm × 600 mm. Steel plate with the dimensions 100 mm × 50 mm ×10 mm was used for the footing. The present numerical of GPA were compared with the experimental results reported by [40]. Table 3 depicts the comparison of results. Study of this table reveals that the variance in the pull-out capacity was about 8.77%. The fact that the parameters for the sand modelling procedure were chosen based on empirical correlation may be the source of this discrepancy in the results.

Table 3. Comparison of the results for the software validation.

Diameter(mm)	Experimental results of Uplift Load (N) for a = 5° and L = 300 mm	Numerical analysis of uplift load (N)for a = 5° and L = 300 mm	% Error in results
30	306.8	287.5	6.29%
45	362.8	327.8	9.65%
60	398.8	357.4	10.38%

5. Results and Discussion

5.1. Effect of GPA diameter on GPA system uplift capacity

A finite element analysis was conducted to analyses the influence of granular pile diameter on GPA system pull-out capacity. GPA of various diameters for lengths of 4, 8, and 12 m are simulated to calculate the pull-out behaviour of GPA system. The GPA system's uplift capability for a 10% specified upward displacement at a $\alpha = 0^{\circ}$ GPA is observed to be 4.2 kN for 0.2 m diameter, 5.55 kN for 0.3 m diameter, 8.64 kN for 0.4 m diameter, 16.1 kN for 0.6 m diameter, 24.42 kN for 0.8 m diameter, and 33.22 kN for 1.2 m diameter, for pile length of 4 m, as shown in Table 4. This showed that the pull-out capability of the GPA system increased as the diameter increases. Same result is showing for 5°, 10°, and 15° inclined GPA. Percentage increase in uplift capacity for $\alpha = 0^{\circ}$ inclined GPA for length 4 m is around 32% when the GPA's diameter is increases from 0.2 m to 0.3 m, 56% when the GPA's diameter is increases from 0.3 to 0.4 m, 86% when the GPA's diameter is increases from 0.4 to 0.6 m, 52% when the diameter of GPA is increases from 0.6 m to 0.8 m, and 36% when the GPA's diameter is increases from 0.8 m to 1.2 m. Similar trend is showing for another inclined angle of GPA. Based on the above FEM analysis results, the increase in uplift resistance is not just due to resistance provided by the pile's self-weight but is also connected to the failure mechanism leading away the edges of the pile surface with the capacity to contribute a large amount of soil as the diameter of the pile increases [29]. Similar result can be seen for other inclination angles as evaluated from the data of table 4, 5, 6 and 7, which are illustrated in Figures 5, 6, and 7 for 0° inclination and pile lengths of 8 m and 12 m.

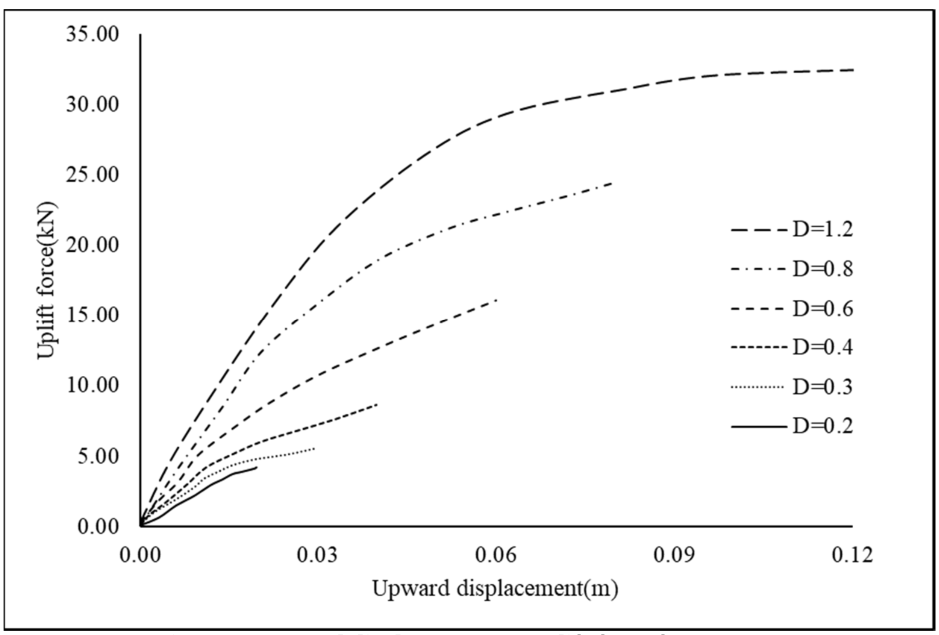


Figure 5. Upward displacement *vs.* uplift force for L = 4 m.

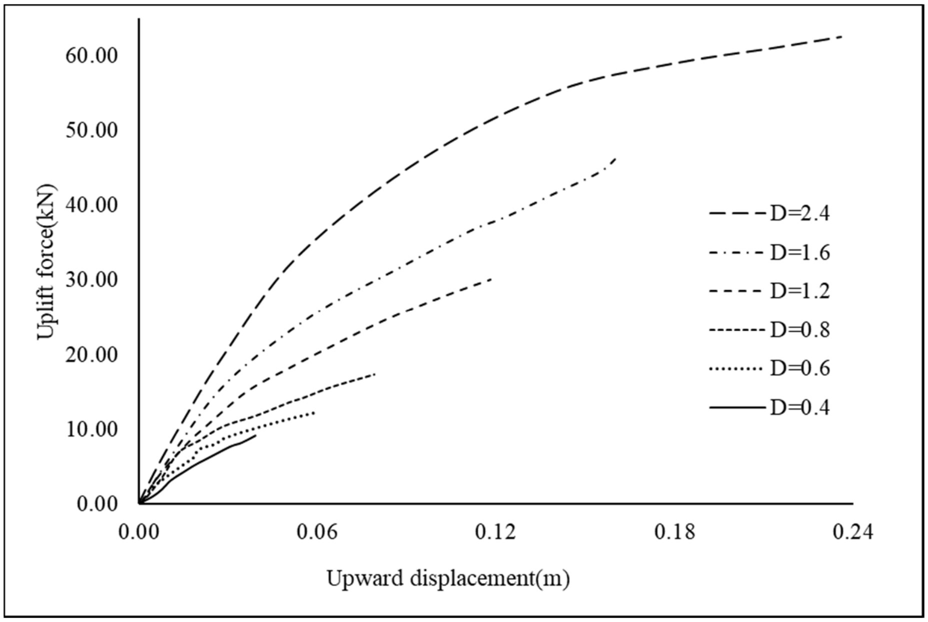


Figure 6. Upward displacement *vs.* uplift force for L = 8 m.

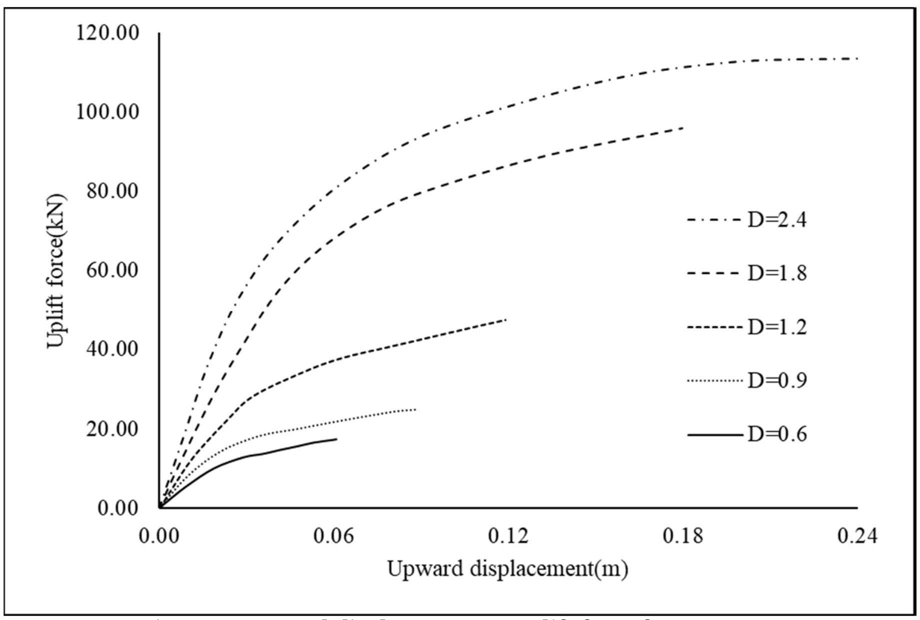


Figure 7. Upward displacement *vs.* uplift force for L = 12 m.

Table 4. Value of uplift capacity of efficiency of GPA for 0˚ pile anchor.

Length (m)	Diameter (m)	L/D ratio	Uplift capacity (kN) single pile	Uplift capacity (kN) double pile at S-2D	Uplift capacity (kN) double pile at S-2.5D	Uplift capacity (kN) double pile at S-3D	Efficiency (η) of double pile at S-2D (%)	Efficiency (η) of double pile at S-2.5D (%)	Efficiency (η) of double pile at S-3D (%)
4	0.2	20	4.20	4.76	6.11	6.98	56.67	72.74	83.10
	0.3	13.33	5.55	7.48	8.63	9.31	67.39	77.75	83.87
	0.4	10	8.64	15.55	16.4	16.97	89.99	94.91	98.21
	0.6	6.67	16.10	27.41	28.22	28.71	85.12	87.64	89.16
	0.8	5	24.42	33.92	34.23	34.72	69.45	70.09	71.09
	1.2	3.33	33.22	39.75	40.34	40.73	59.83	60.72	61.30
8	0.4	20	9.20	14.26	15.82	16.84	77.50	85.98	91.52
	0.6	13.33	12.25	19.1	21.56	22.17	77.96	88.00	90.49
	0.8	10	17.40	30.89	31.93	32.45	88.76	91.75	93.25
	1.2	6.67	30.02	46	46.55	47.15	76.62	77.53	78.53
	1.6	5	46.11	54.55	55.48	56.4	59.15	60.16	61.16
	2.4	3.33	62.50	68.75	70	71.25	55.00	56.00	57.00
12	0.6	20	17.34	28.36	29.84	30.44	81.78	86.04	87.77
	0.9	13.33	24.88	42.75	45.43	46.02	85.91	91.30	92.48
	1.2	10	47.47	86.5	90.65	93.24	91.11	95.48	98.21
	1.8	6.67	95.85	116.48	118	118.55	60.76	61.55	61.84
	2.4	5	113.42	120.04	123.01	123.61	52.92	54.23	54.49

Table 5. Value of uplift capacity of efficiency of GPA for 5˚ pile anchor.

Length (m)	Diameter (m)	L/D ratio	Uplift capacity (kN) single pile	Uplift capacity (kN) double pile at S-2D	Uplift capacity (kN) double pile at S-2.5D	Uplift capacity (kN) double pile at S-3D	Efficiency (η) of double pile at S-2D (%)	Efficiency (η) of double pile at S-2.5D (%)	Efficiency (η) of double pile at S-3D (%)
4	0.2	20	4.52	5.35	6.80	7.74	59.17	75.24	85.60
	0.3	13.33	5.98	8.35	9.59	10.33	69.89	80.25	86.37
	0.4	10	9.28	16.89	17.80	18.23	90.99	95.91	98.21
	0.6	6.67	17.08	29.98	30.80	31.32	87.74	90.14	91.66
	0.8	5	25.47	36.65	36.98	37.49	71.95	72.59	73.59
	1.2	3.33	33.92	42.28	42.88	43.28	62.33	63.22	63.80
8	0.4	20	9.90	15.84	17.52	18.61	80.00	88.48	94.02
	0.6	13.33	13.12	21.11	23.75	24.40	80.46	90.50	92.99
	0.8	10	18.69	34.03	35.13	35.50	91.04	94.00	94.99
	1.2	6.67	31.88	50.45	51.03	51.67	79.12	80.03	81.03
	1.6	5	48.18	59.25	60.22	61.18	61.48	62.49	63.49
	2.4	3.33	63.94	73.53	74.81	75.45	57.50	58.50	59.00
12	0.6	20	18.69	31.51	33.10	33.94	84.28	88.54	90.77
	0.9	13.33	26.90	46.48	49.65	50.29	86.41	92.30	93.48
	1.2	10	50.98	93.92	98.38	100.14	92.11	96.48	98.21
	1.8	6.67	102.08	129.16	130.77	131.36	63.26	64.05	64.34
	2.4	5	118.75	132.81	134.73	135.36	55.92	56.73	56.99

Table 6. Value of uplift capacity of efficiency of GPA for 10˚ pile anchor.

Length (m)	Diameter (m)	L/D ratio	Uplift capacity (kN) single pile	Uplift capacity (kN) double pile at S-2D	Uplift capacity (kN) double pile at S-2.5D	Uplift capacity (kN) double pile at S-3D	Efficiency (η) of double pile at S-2D (%)	Efficiency (η) of double pile at S-2.5D (%)	Efficiency (η) of double pile at S-3D (%)
4	0.2	20	4.53	5.58	7.04	7.98	61.67	77.74	88.10
	0.3	13.33	5.99	8.67	9.61	10.34	72.39	80.25	86.37
	0.4	10	9.31	17.14	17.96	18.29	91.99	96.41	98.21
	0.6	6.67	17.19	30.52	31.34	31.87	88.74	91.14	92.66
	0.8	5	25.67	38.22	38.54	39.06	74.45	75.09	76.09
	1.2	3.33	34.28	44.45	45.06	45.46	64.83	65.72	66.30
8	0.4	20	9.93	16.38	17.86	18.87	82.50	89.98	95.02
	0.6	13.33	13.24	21.97	24.23	24.89	82.96	91.50	93.99
	0.8	10	18.76	34.90	35.92	36.39	93.04	95.75	96.99
	1.2	6.67	32.09	52.38	52.97	53.61	81.62	82.53	83.53
	1.6	5	48.51	62.07	63.05	64.50	63.98	64.99	66.49
	2.4	3.33	64.64	100.20	78.87	79.51	77.50	61.00	61.50
12	0.6	20	18.73	32.31	34.10	34.37	86.28	91.04	91.77
	0.9	13.33	26.92	47.06	49.96	50.60	87.41	92.80	93.98
	1.2	10	51.17	94.78	99.26	100.51	92.61	96.98	98.21
	1.8	6.67	102.66	135.02	136.64	137.23	65.76	66.55	66.84
	2.4	5	119.77	139.94	141.88	142.51	58.42	59.23	59.49

Table 7. Value of uplift capacity of efficiency of GPA for 15˚ pile anchor

Length (m)	Diameter (m)	L/D ratio	Uplift capacity (kN) single pile	Uplift capacity (kN) double pile at S-2D	Uplift capacity (kN) double pile at S-2.5D	Uplift capacity (kN) double pile at S-3D	Efficiency (η) of double pile at S-2D (%)	Efficiency (η) of double pile at S-2.5D (%)	Efficiency (η)of double pile at S-3D (%)
4	0.2	20	4.48	5.39	6.88	7.81	60.17	76.74	87.10
	0.3	13.33	5.93	8.46	9.34	10.12	71.39	78.75	85.37
	0.4	10	9.21	16.76	17.67	18.00	90.99	95.91	97.71
	0.6	6.67	16.99	29.64	30.62	30.97	87.24	90.14	91.16
	0.8	5	25.32	37.20	37.52	38.03	73.45	74.09	75.09
	1.2	3.33	34.02	43.43	44.03	44.43	63.83	64.72	65.30
8	0.4	20	9.83	16.02	17.49	18.51	81.50	88.98	94.22
	0.6	13.33	13.10	21.47	23.70	24.35	81.96	90.50	92.99
	0.8	10	18.55	34.14	35.20	34.87	92.04	94.90	93.99
	1.2	6.67	31.73	50.84	51.42	52.06	80.12	81.03	82.03
	1.6	5	47.91	59.87	60.84	62.75	62.48	63.49	65.49
	2.4	3.33	64.19	97.57	76.38	77.03	76.00	59.50	60.00
12	0.6	20	18.57	31.49	33.26	33.34	84.78	89.54	89.77
	0.9	13.33	26.62	45.74	48.61	49.51	85.91	91.30	92.98
	1.2	10	50.60	92.21	97.14	98.38	91.11	95.98	97.21
	1.8	6.67	101.51	129.44	132.07	133.66	63.76	65.05	65.84
	2.4	5	117.96	134.28	136.19	137.99	56.92	57.73	58.49

5.2. Effect of GPA length on GPA system uplift capacity

Various L/D ratios, as shown in Table 4, are taken into consideration to examine the pull-out behaviour of GPA, and related uplift is determined by applying a specified displacement of 10% of D. It has been shown that an anchor pile's uplift capability increases with length of GPA. This is related to own weight of a GPA system and an increment in the amount of friction mobilised along the pile-soil interface. For a fixed pile length of 4 m, the model showed a very slowly increasing pattern as in uplift capacity on a decreasing L/D ratio, as shown in Fig 8. For an 8 m length of the pile has a little larger uplift capacity than the 4 m length of the pile; after that, the pull-out capacity drastically changes as pile length goes from 8 to 12 m, as shown in Figure 8. According to the results of the present model, lengthening the anchor pile increased the GPA system's surface area and own weight, which contributed to the system's increased resistance to the uplift forces. Similar results are observed for other inclination angles, as shown in Tables 5, 6, and 7.

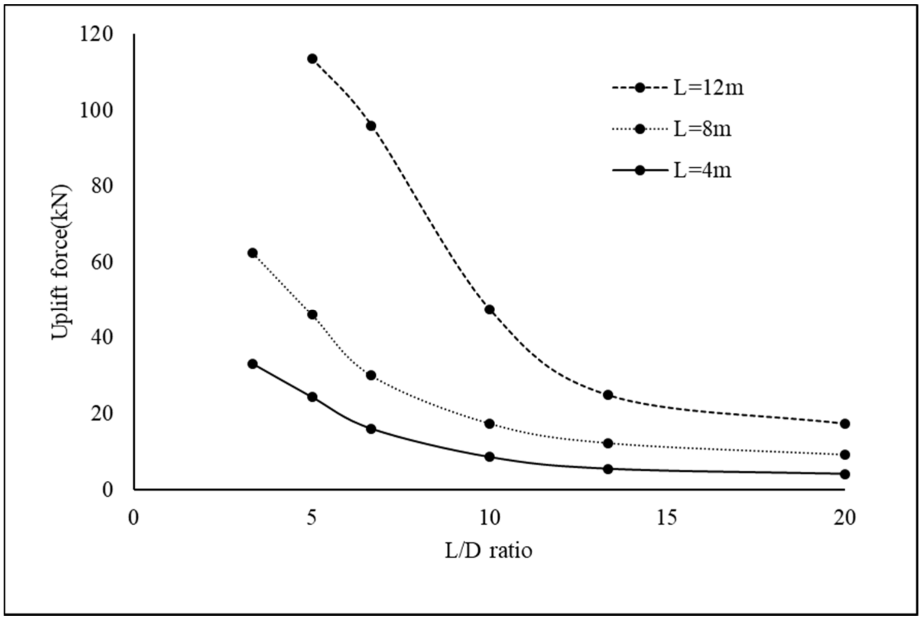


Figure 8. L/D ratio *vs.* uplift force of GPA.

5.3. Effect of GPA inclination on GPA system uplift capacity

Different inclined angles 5°, 10°, and 15° that are used are provided in Table 1. The uplift capacity for a length of 4 m of a L/D ratio 10 at $\alpha = 0^{\circ}$ is 8.64 kN, for $\alpha = 5^{\circ}$ is 9.28 kN, for $\alpha = 10^{\circ}$ is 9.31 kN, and for $\alpha = 15^{\circ}$ is 9.21 kN. Percentage increase is 7.41% for $\alpha = 0^{\circ}$ to 5°, 0.32% for $\alpha = 5^{\circ}$ to 10°, -1.1% for $\alpha = 10^{\circ}$ to 15°. From the above results it can be evaluated that there is increment in uplift capacity of GPA when the angle of inclination is increases from $\alpha = 0^{\circ}$ to 5° and increment is slow when the angle of inclination is increases from $\alpha = 5^{\circ}$ to 10°. The uplift capacity has decreased when the angle of inclination is increases from $\alpha = 10^{\circ}$ to 15°. The above results show that 10° is the optimum angle of inclination. A similar trend can be seen for other pile lengths and diameters for inclined angle such as $\alpha = 5^{\circ}$, 10°, and 15°, as illustrated in Figure 9 and in Tables 4, 5, 6, and 7.

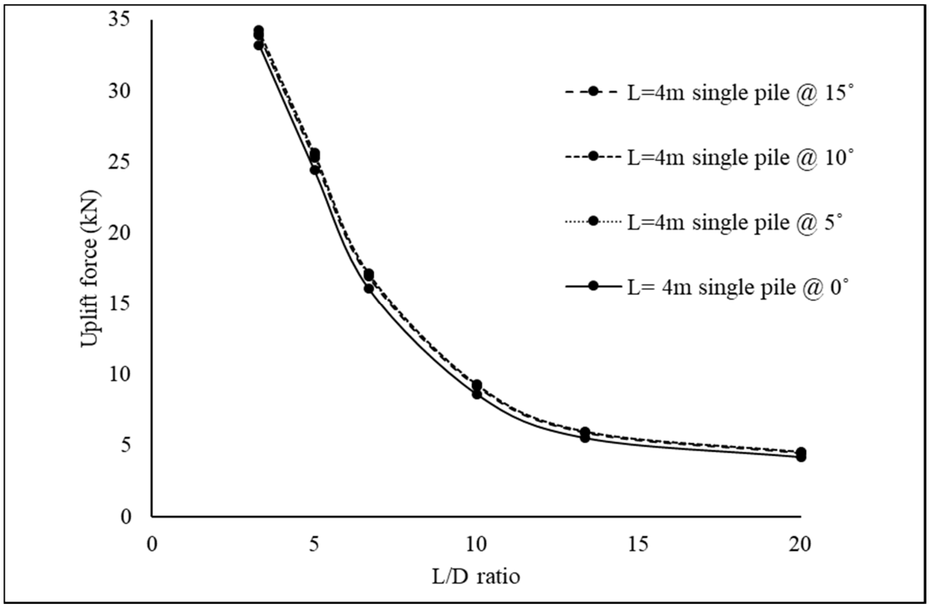


Figure 9. L/D ratio *vs.* uplift force at different values of inclination angle of single pile for L = 4 m.

5.3.1. Effect of GPA inclination on group of granular pile anchor

For a length of 4 m and spacing of pile 2D, the pull-out capacity at different L/D ratios for various inclined angles that are $\alpha = 0^{\circ}$, 5°, 10°, and 15° is shown in Figure 10. The graph depicts that there is an increase in the uplift capacity with the inclination of the GPA. However, the increment with inclination is justifiable for small L/D ratios, i.e. up to 6.67 after that the increment in uplift capacity with inclination is very small as L/D ratio increases, as illustrated in Figure 10 and Tables 4, 5, 6, and 7. From this graph results it can be evaluated that there is increment in uplift force till inclined angle $\alpha = 10^{\circ}$, and after that there is decrement in values of uplift capacity. The effect of diameter on inclination of group of GPA can also be revealed in Figure 10. As we increase the diameter for a fixed length, the uplift capacity increases for every inclination angle of the pile. A similar trend can be seen for other pile lengths, diameters, and spacing for inclined angle such as $\alpha = 5^{\circ}$, 10°, and 15°, as illustrated in Figure 10 and in Tables 4, 5, 6, and 7, where S denotes the spacing between two piles that is varied from 2D to 3D.

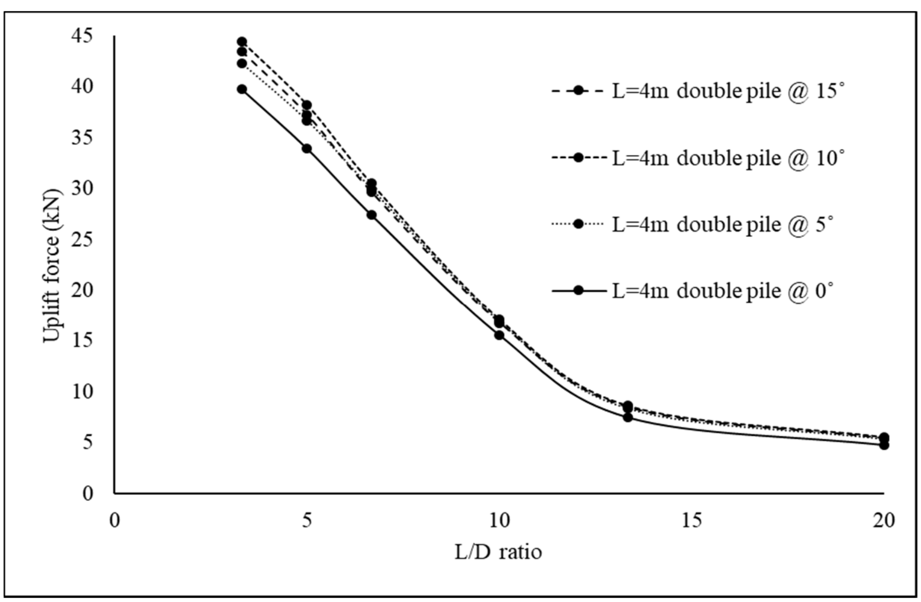


Figure 10. L/D ratio *vs.* uplift force at different values of inclination of double pile for L = 4 m.

5.3.2. Effect of GPA inclination on efficiency of group of granular pile anchor

At a pile length of 4 m and a pile group spacing of 2D, Figure 11 shows the efficiency for different L/D ratios for various inclined angles. For a diameter 0.2 m the efficiency is 56.67% for 0°, efficiency is 59.17% for 5°, efficiency is 61.67% for 10°, efficiency is 60.17% for 15°. These results show an increment of 4.41% for $\alpha = 0^\circ$ to 5°, increment of 4.23% for $\alpha = 5^\circ$ to 10°, decrement of - 2.43% for $\alpha = 10^\circ$ to 15°. From this graph results it can be evaluated that there is increment in efficiency from $\alpha = 0^\circ$ to 5°, $\alpha = 5^\circ$ to 10°, and after that there is decrement in values of uplift capacity from $\alpha = 10^\circ$ to 15°. Hence, we can conclude that 10° is the optimum angle of inclination. A similar trend can be seen for other pile lengths, diameters and spacing for inclined angle such as $\alpha = 5^\circ$, 10°, and 15°, as illustrated in Figure 11 and in Tables 4, 5, 6, and 7.

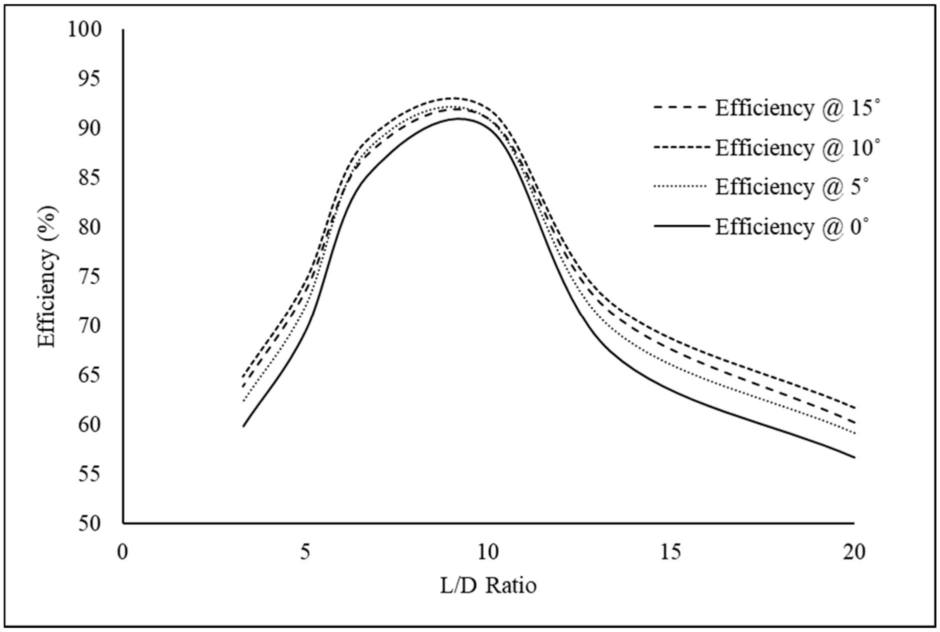


Figure 11. L/D ratio *vs.* efficiency at different values of inclination angle of double pile for L = 4 m.

5.4. Effect of group of granular piles anchor (GPA's)

A set of two GPAs with variable L/D ratios are subjected to a finite element analysis with pile length of 4,8 and 12 m and inclined angles of α = 0°, 5°, 10°, and 15° with spacing of 2D, 2.5D, and 3D, and estimate the pull-out capacity. In order to compare the uplift behaviour of single and group piles, the uplift capacity of a single pile in a group is calculated by dividing the uplift capacity of a group of piles by the number of piles in a set. According to the graph the load per pile in a pile group and an individual pile have the same shape of curves. Tables 4, 5, 6, and 7 summarise the differences in the uplift capacity of a GPA system for individual piles and groups of piles placed in 2D, 2.5D, and 3D with an inclined angle of 0°, 5°, 10°, and 15°. Each L/D ratio for fixed length shows the uplift capability of the pile group in increasing order, when the pile spacing was raised from 2D to 3D, as illustrated in Figure 11. Additionally, it is shown that the uplift capacity for 4m of GPA remains almost constant when the spacing increases from 2.5D to 3D. It can be explained by the fact that as the space between the two bordering GPAs is increased above 2.5D, the pressure bulb of individual pile no longer overlap, and as a result, mobilisation of uplift capability beyond that spacing is minimal. Similar outcomes were achieved for further pile lengths of 4 m, 8 m and 12 m at $\alpha = 0^\circ$ are shown in Figures 12, 13, and 14. Similar results will be for other inclined GPA for different lengths, diameters and spacing that are shown in Table 4, 5, 6, and 7.

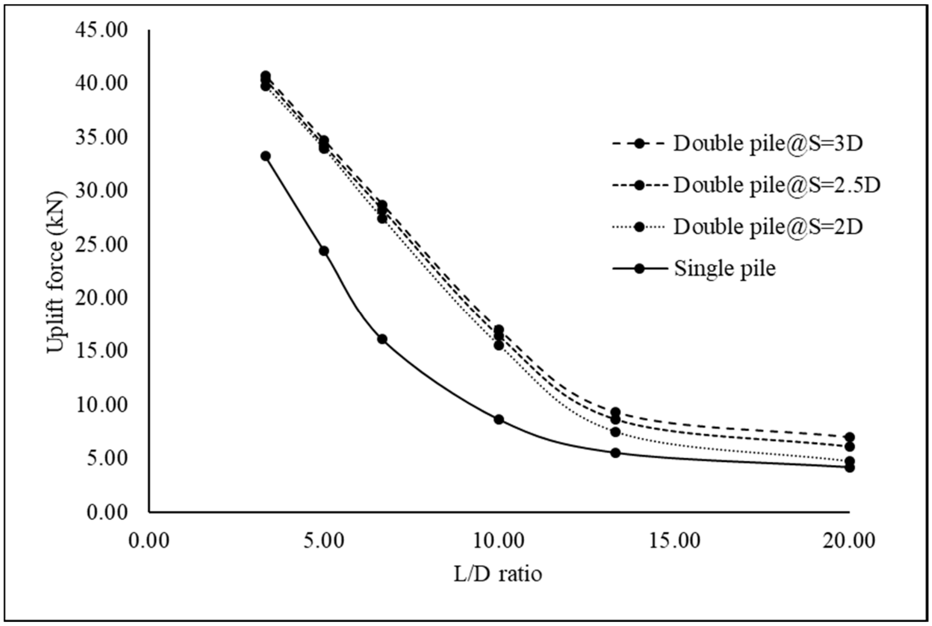


Figure 12. L/D ratio *vs.* uplift force for L = 4 m.

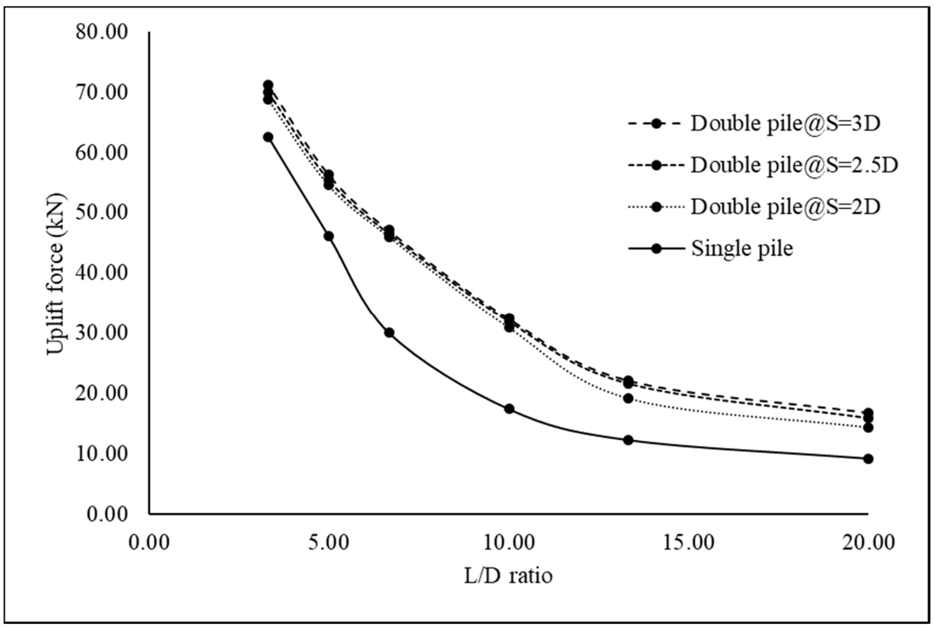


Figure 13. L/D ratio *vs.* uplift force for L = 8 m.

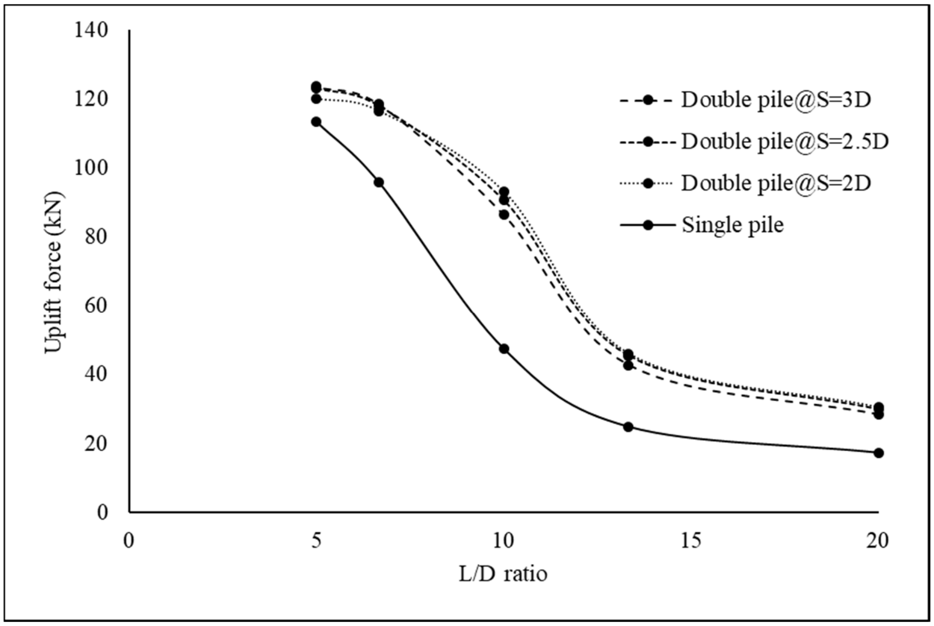


Figure 14. L/D ratio *vs.* uplift Force for L = 12 m.

5.5. Effect of L/D ratio on efficiency of group of granular pile anchor

According to [20], the efficiency of the GPA system is determined for a specified upward displacement and is expressed as:

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

The effect of the L/D ratios (for a fixed lengths of GPA) on the effectiveness of the pile group at varying spaced data is shown in Figure 15. The graph's results show that for a fixed GPA length, for $\alpha = 0^{\circ}$ and an increasing L/D ratio of 3.33 to 5, 6.67 to 10, and 6.67 to 10, consecutively, efficiency of piles improved. Efficiency value decreased when L/D ratio increased from 10 to 13.33 and 13.33 to 20, successively, with relation to the 2D, 2.5D, and 3D spaced values. Same conclusions were made for the other GPA lengths at equivalent spaced values, and are shown in Tables 4, 5, 6, and 7. There is barely any difference in the effectiveness of the GPA system when the spacing is raised from 2.5D to 3D, showing that 2.5D is the optimal spacing value for the GPA system. Same efficiency conclusion is found for the GPA lengths of 8 m and 12 m, as shown in Figures 16 and 17, and similar results are to be for all other inclined angles that are $\alpha = 5^{\circ}$, 10°, and 15°.

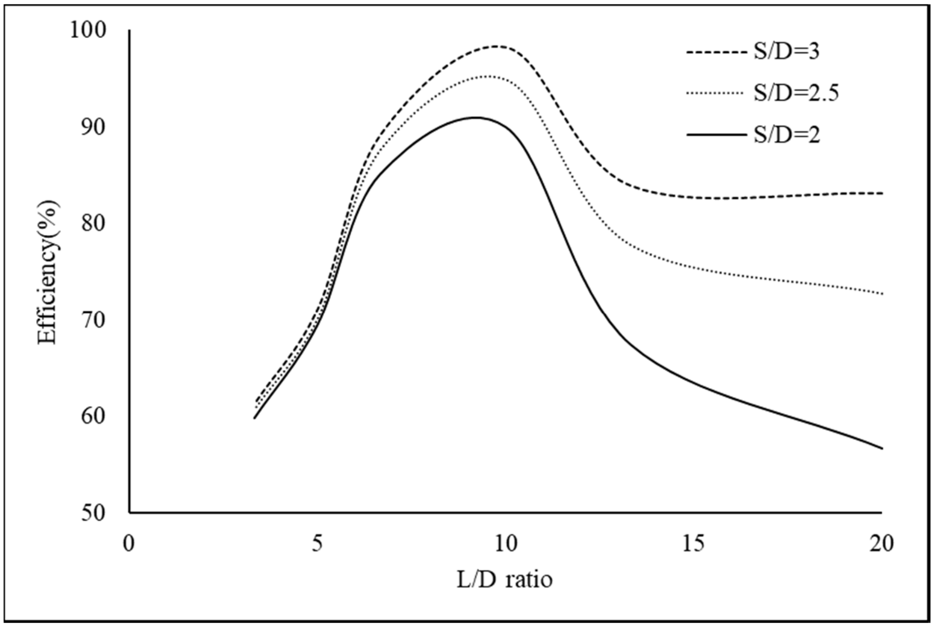


Figure 15. L/D ratio *vs.* efficiency for L = 4 m.

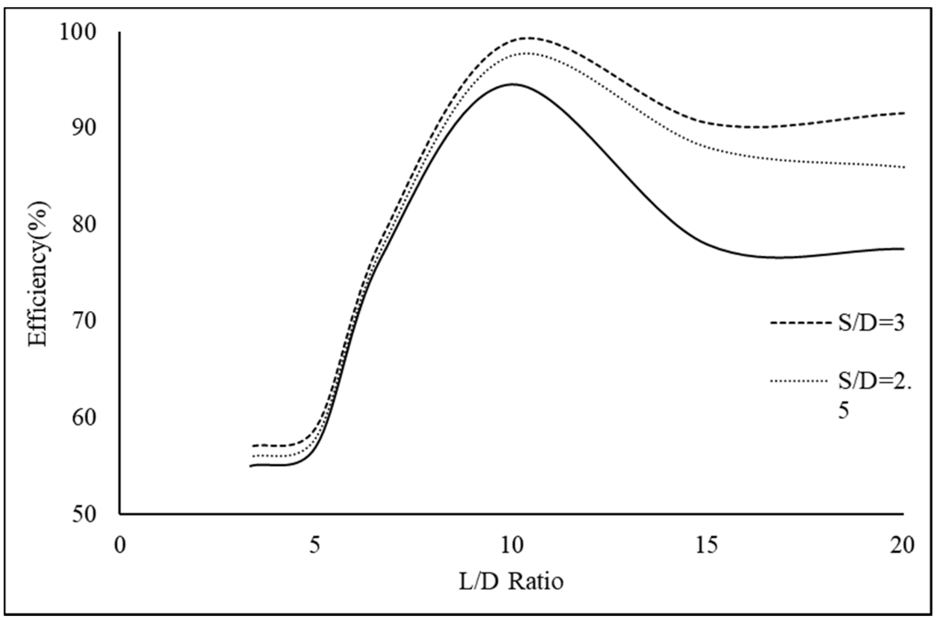


Figure 16. L/D ratio *vs.* efficiency for L = 8 m.

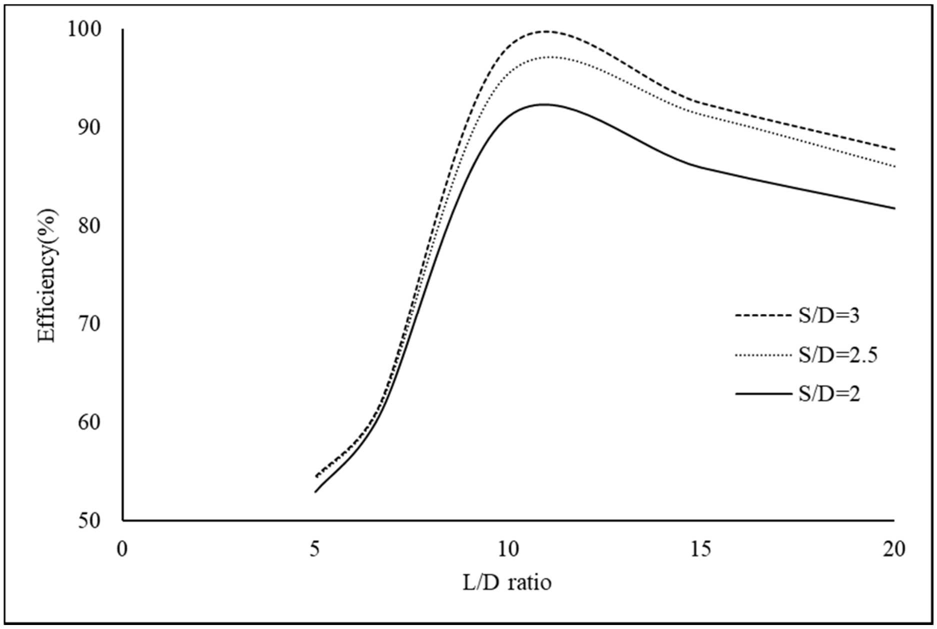


Figure 17. L/D ratio *vs.* efficiency for L = 12 m.

5.6. Stress and displacement contours

Due to the application of uplift force in the form of specified vertical displacement to the GPA stresses develop in the adjoining expansive clay. This can be attributed to the fact that the GPA is held in between the expansive soil with some friction between them. Moreover, the property of expansive clay to expand with time imparts radial stresses on the GPA and hold the GPA in its position. The stress and displacement contours developed for length 4 m are shown in the Figure 18 for vertical GPA with single pile anchor as well as double pile anchor. The stress and displacement contours also show the failure pattern of the soil due to uplift force. The stress distribution for each scenario stayed within the defined lateral and vertical bounds taken into account by the numerical analysis. The double pile anchor which is at 2D spacing as shown in Figure 18 (b) distributes the stresses over a larger area as compared to the single pile anchor as shown in Figure 18 (a). The stresses in the both Figure 18 (a) and (b) are almost similar due to the same fact that as in the double pile anchor the uplift force as well as area increases simultaneously and since both are related to the stress the net result is no change in stress value. The displacement contours in fig 18 (c) and (d) shows that the surrounding soil also gets displaced with the displacement in the GPA revealing that the expansive clay also provides resistance to the uplift capacity of the anchor. The dark red colour shows high value of stress and displacement developed respectively while the faint blue colour indicates decrease in stress and displacement value which decreases as the distance from the GPA increases.

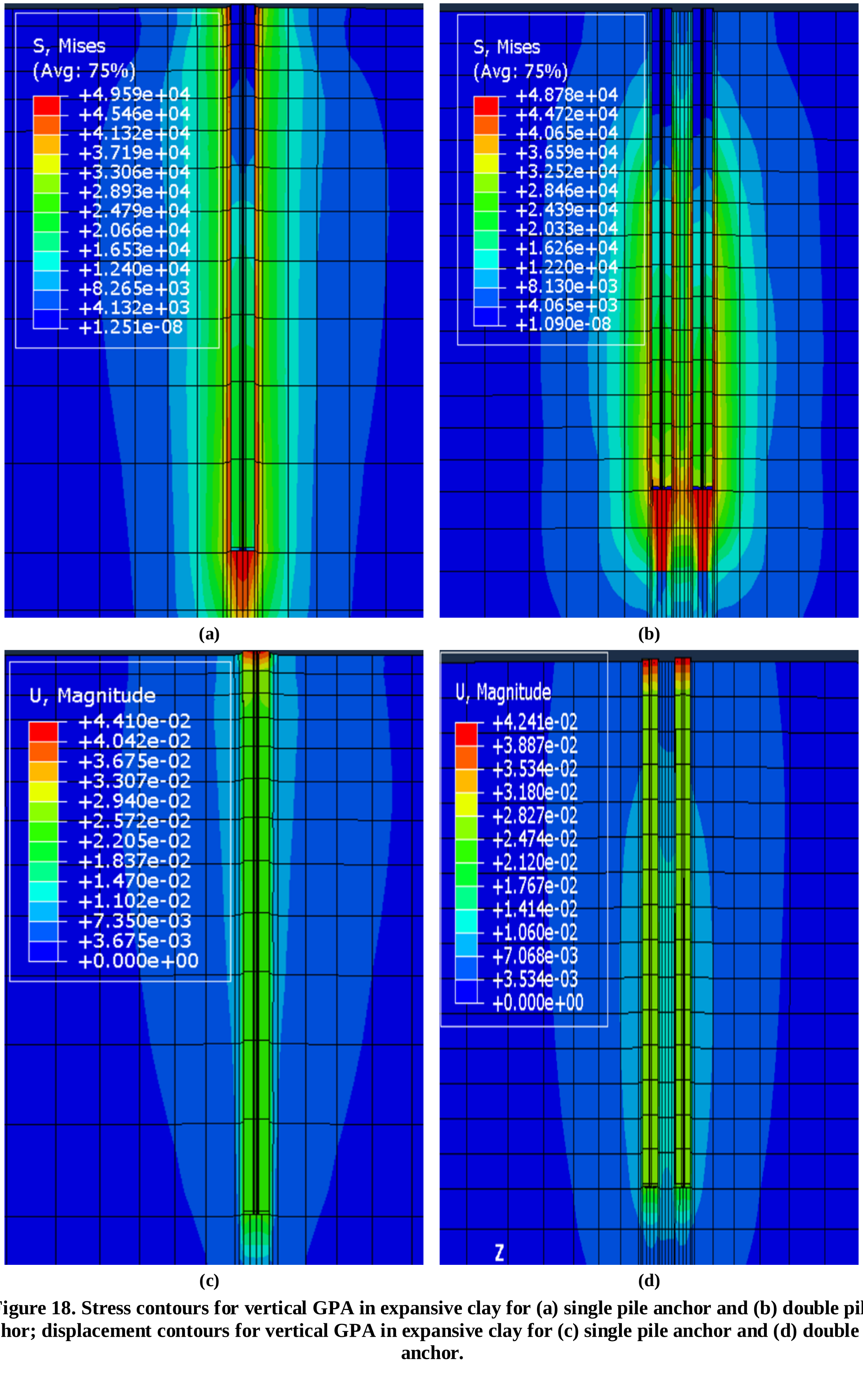


Figure 18. Stress contours for vertical GPA in expansive clay for (a) single pile anchor and (b) double pile anchor; displacement contours for vertical GPA in expansive clay for (c) single pile anchor and (d) double pile anchor.

6. Conclusions

The potential of GPA against pull-out force was predicted numerically by providing a specified displacement of 10 % of piles diameter at centre of piles top for various pile arrangements. Graphical representations were used to show the uplift capacity and associated upward displacement. From the study mentioned above, the following key findings can be evaluated:

1. Due to the own weight of the pile and friction that generated at the pile-soil interface, the GPA system's pull-out resistance in expansive soil improved as the pile's length and diameter increased.
2. With varying L/D ratios for single GPA and group GPA, while keeping length fixed, uplift capacity improved with decreasing L/D ratios due to increasing surface area.
3. When the spacing was changed from 2D to 2.5D and 2.5D to 3D, the group pile's uplift capacity increased. The pull-out capacity value increased by 5.47% when the S/D ratios increased from 2 to 2.5, and by 3.48% when the ratios increased from 2.5 to 3. Result showed a little increase in percentage of pull-out capacity as spacing was increased beyond 2.5D. Hence, 2.5D was found to be the optimum spacing between two piles for group action. This is due to the fact that as spacing between two adjacent GPAs increases above 2.5D, the pressure bulb of individual piles no longer overlap, and mobilisation of uplift capability is minimal beyond that spacing.
4. For different length up to L/D ratios 10, capability of pile group improved with increasing L/D ratios. After that, the efficiency started to decreases, and an optimum L/D ratio is around 10.
5. The pull-out capacity of GPA increased if the angle of inclination (α) increases from $\alpha = 0^{\circ}$ to 10°. After that there is decrement in pull-out capacity when α increases from 10° to 15°. If the angle of inclination (α) is increased from 0° to 5°, the uplift capacity for a 4 m length of a pile with a L/D ratio of 10 increases by about 7.41%, from 5° to 10° by about 0.32%, and from 10° to 15° by about -1.1%. From the above result, it can be concluded that the optimum angle of inclination $\alpha = 10^{\circ}$.

Notations

c	Cohesion of soil
D	Diameter of pile anchor
E	Modulus of elasticity
L	Length of pile anchor
S	Spacing between pile anchors
L/D	Embedment ratio
γ	Unit weight of soil
ϕ	Internal friction angle
υ	Poisson ratio
η	Efficiency of group pile anchor
α	Angle of inclination with respect to vertical

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Conflict of interest

The authors declare that they have no conflict of interest.

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تحلیل عددی لنگر شمع دانه‌ای شیبدار تحت نیروهای بالابرنده در خاک منبسط با استفاده از Abaqus

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چکیده:

لنگر شمع دانه‌ای یک تکنیک جدید است که معمولاً برای بهبود مقاومت در برابر کشش خاک گسترده مانند خاک رس نرم، ماسه شل و خاک پنبه سیاه استفاده می‌شود. با استفاده از نرم افزار Abaqus، این کار یک بررسی عددی برای تخمین ظرفیت کشش لنگر شمع دانه‌ای در خاک رس نرم ارائه می‌دهد. با اعمال یک جابجایی مشخص 10٪ از D (قطر شمع) روی لنگر شمع دانه‌ای، اثرات طول، قطر، زاویه شیب (α) و تعداد GPA در مقادیر فاصله متفاوت بر ظرفیت بالابر بررسی می‌شود. علاوه بر این، نسبت L/D شمع‌های فردی و گروهی با استفاده از متغیرهای مختلف مورد بررسی قرار می‌گیرد. این مطالعه از خاک گسترده و معدل وزن واحد 17 کیلونیوتن بر متر مکعب و 22 کیلو نیوتن بر متر مکعب، نسبت پواسون 0/4 و 0/3، مدول کشش 4 مگاپاسکال و 11 مگاپاسکال برای تخمین ظرفیت بالا بردن استفاده می‌کند. مقدار چسبندگی برای رس منبسط 25 کیلو پاسکال و زاویه مقاومت برشی برای 36 GPA درجه است. با توجه به مطالعه عددی، هم برای یک شمع و هم برای شمع های قرار داده شده در یک گروه، با افزایش طول و قطر شمع، قابلیت بیرون کشیدن لنگر شمع دانه‌ای بهبود می‌یابد. برای یک شمع قرار داده شده در گروه، مقدار ظرفیت خروجی زمانی که فاصله (s) 2.5D باشد، نتیجه بهینه را نشان می‌دهد. علاوه بر این، ظرفیت بالابرنده لنگر شمع دانه‌ای با افزایش شیب زاویه (α) از 0° به 10° افزایش می‌یابد و سپس از 10° به 15° کاهش می‌یابد. کارایی GPA مورد بررسی قرار می‌گیرد که به انتخاب پارامترهای مختلف لنگر شمع دانه‌ای کمک می‌کند.

کلمات کلیدی: لنگر شمع دانه‌ای، مقاومت در برابر کشش، خاک گسترده، جابجایی رو به بالا، ظرفیت بالا بردن.