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Shallow Foundation Stability on Expansive Clay Using Group Granular Pile Anchor

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Abstract

Expansive soil is problematic because it undergoes significant volume changes, swelling when it absorbs moisture and shrinking when it dries out. This characteristic can lead to serious structural issues for buildings, roads, and other infrastructure. The solution to this problem is to use a Granular Pile Anchor (GPA) system, an innovative foundation technique that employs a steel anchor extending from a shallow foundation and embedded in a granular pile at depths below expansive soil layers. This enhances the load-bearing capacity, providing additional resistance to uplift and lateral loads in expansive soil. The effectiveness of GPA in overcoming uplift forces on structures can be further improved by studying its optimum design. Therefore, this research presents a comprehensive design that incorporates a group pile system on the GPA, compared with varying steel anchor lengths and diameters, to mitigate heaving using the 3D finite element software PLAXIS. Heave and uplift forces reduction was obtained through varying dimensional input parameters from the ratio of GPA length to the expansive soil layer thickness (L/H), the area replacement ratio (Ar), which is the ratio of the foundation footing area to GPA cross-section area, and the number of group GPA (N). The results indicated that with L/H = 1.5, where the length of GPA extends partly in the expansive soil, and N = 3, the heave and the uplift forces were reduced to 92.55% and 92.79%, respectively. These improvements were sufficient for the optimum performance of the GPA structure. This indicates the significant improvement in the performance of the shallow foundation in mitigating heaving problems caused by expansive soil with the application of group GPA.

1. Introduction

A foundation structure is a crucial component in building construction. In some cases, foundations must be built on unsuitable soil, such as expansive soil. These soils are widespread, particularly in arid regions, where they undergo cycles of swelling when wet and shrinking when dry, leading to significant structural challenges [1].

Expansive soils, known for their tendency to expand with moisture and contract as they dry, can cause severe foundation instability, structural damage, and financial losses [2]-[5]. Due to their sensitivity, foundations on expansive soils require specialised design.

Mitigating the issues posed by expansive soils remains a significant concern in the construction industry. Several techniques have been proposed and implemented to mitigate the damage caused by expansive soils, including pre-wetting [6], wetting-drying cycles [7], chemical treatment [8]-[10], and soil reinforcement [11]. However, these methods do not fully address the challenges posed by expansive soils and may not always be practical or may introduce new issues.

Traditional mitigation strategies often involve expensive foundation designs, such as deep piling or moisture control for expansive soils, which are not always economically or environmentally sustainable. Even granular piles (stone columns), while effective at improving bearing capacity, cannot counteract the uplift forces induced by expansive soils, which consist of particulate materials that cannot resist tensile forces. To address these limitations, an innovative solution has been introduced: granular pile anchors (GPA).

Granular pile anchors (GPA) are a geotechnical solution that combines soil stabilisation with foundation support, providing a cost-effective, sustainable way to combat the effects of expansive soils. This technique involves installing piles of granular material, such as sand or gravel, deep into the ground to anchor the foundation. The main benefits of using GPA include enhanced stability and reduced ground movement due to expansive soils [12].

Although numerous studies have examined the resistance of GPA under external pullout forces, which was investigated by Johnson & Sandeep [13], O'Kelly et al. [14], Sivakumar et al. [15], Sharma et al. [16], Rao et al. [17], Kranthikumar et al. [18], Izzati [19], and Ganasan et al. [20], none have comprehensively looked at comparing design parameters that incorporate a group Granular Pile Anchor system.

This research aims to develop an alternative approach that incorporates a group pile system for GPA foundations to mitigate soil heave, using numerical modelling with the 3D finite element software PLAXIS. The analysis focuses on key design input parameters, including the ratio of GPA length to expansive soil layer thickness (L/H), the area replacement ratio (Ar), the ratio of the foundation footing area to the GPA cross-sectional area, and the number of anchor piles (N). These parameters strategically compare anchor rod length (L) and anchor plate diameter (D) measurements with the number of anchor piles used to study the effect on GPA performance. GPA performance is evaluated through the heave measurement of the foundation system and its uplift forces. This new design approach in this research will serve as a reference for improved shallow foundation design by incorporating group piles, helping minimise maintenance and repair costs associated with soil heaving.

2. Experimental Set Up

2.1 Materials Used for Analysis

The soil materials used in this study were classified as expansive clay and were obtained from a construction site in Musayyib, Babil Province, Iraq. This site is known for its significant expansion and shrinkage characteristics. Soil samples were obtained from depths of 0.5 to 2 meters below the original ground surface, specifically from the unsaturated soil layer during the dry arid season. These samples were then sent to a laboratory to determine key expansive clay parameters, such as unit weight, stiffness, and cohesion, needed for numerical modelling analysis.

Fig. 1 illustrates the GPA system consisting of specific anchor rod lengths (L) and anchor plate diameters (D) extended from a shallow foundation. The active zone where heaving or expansion occurs is classified as unsaturated expansive clay soils, and its depth varies by location and conditions. In this research, a depth (H) of 4 m of the active zone containing unsaturated expansive clay and a stable zone of saturated expansive clay of 16 m is simulated. The experimental testing was designed with a specific range of granular pile anchor (GPA) dimensions to capture a variety of outcomes, highlighting the foundation's behaviour under heaving and uplift forces.

Table 1 provides details of the GPA dimensions in terms of the design parameters L/H, Ar, and N. Note that the footing has a diameter (d1) of 2 meters. For the group GPA, the footing diameter (d2) is set to 2.5 m to provide sufficient spacing for the anchor rods, which are placed 1 m apart. The pile anchor, which is attached to the footing, was extended to different lengths that extend to the stable zone. The pile anchor arrangements incorporated as a group are shown in Fig. 2, consisting of three arrangement types based on the number of rods (N =2, 3 and 4).

Standard sand parameters were applied for the granular pile materials used to support the anchor system. A summary of all soil input parameters is provided in Table 2. Additionally, the materials used for the shallow footing and anchor system (plate and rod) were assumed to be steel, with typical rigid-steel properties as outlined in Table 3.

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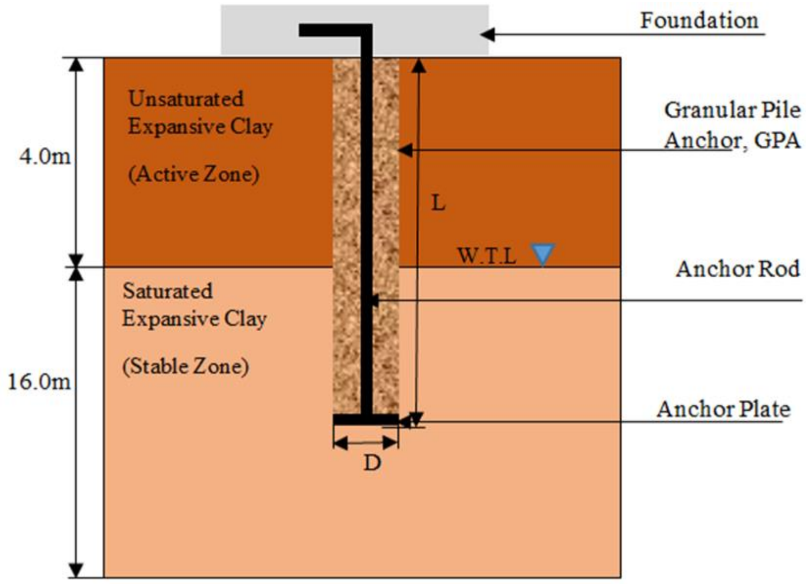

Fig. 1 *The granular pile anchor model diagram*

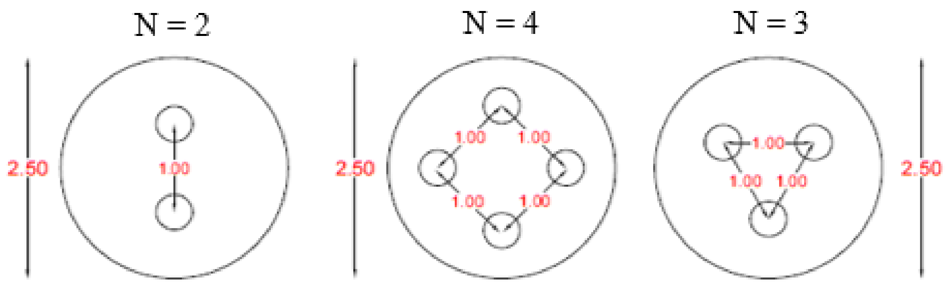

Fig. 2 *The pile anchor arrangements incorporated as a group*

Table 1 *Summary of the GPA dimension and design parameters*

Diameter, D (m)	Length, (L)	L/H	N	Ar
Footing rests on clay with a diameter (d_1 = 2 m)				
	4	1.00		25.0
0.4	6	1.50		25.0
	8	2.00		25.0
	4	1.00		11.1
0.6	6	1.50		11.1
	8	2.00		11.1
	4	1.00	1	6.3
0.8	6	1.50		6.3
	8	2.00		6.3
	4	1.00		4.0
1	6	1.50		4.0
	8	2.00		4.0
Footing rests on clay with a diameter (d_2 = 2.5 m)				
	4	1	2	19.53
0.4	4	1	3	13.02
	4	1	4	9.77

Diameter, D (m)	Length, (L)	L/H	N	Ar
Footing rests on clay with a diameter (d_2 = 2.5 m)				
	6	1.5	2	19.53
	6	1.5	3	13.02
	6	1.5	4	9.77
	8	2	2	19.53
	8	2	3	13.02
	8	2	4	9.77

Table 2 *Summary of all the input parameters*

Model Parameters	Expansive Clay Un-drained Behaviour	Granular Pile Sand Drained Behaviour
γ_{unsat} (kN/m^3)	16.33	17
γ_{sat} (kN/m^3)	19	20
E (kN/m^2)	-	70 x10^3
E_{oed}^{ref} (kN/m^2)	3000	-
E_{50} (kN/m^2)	3500	-
C' (KN/ m^2)	30	3
(ǿ)°	22	42
Volumetric strain% (swelling)	6.6	-
νu	-	0.25

Table 3 *Summary of steel properties used to simulate the footing, anchor plate and rod*

Model Type	Model Parameters	Footing Model Steel	Anchor Plate Steel	Anchor Rod Steel
Linear Elastic	E (kN/m^2)	2x10^6	2x10^6	2x10^6
	ν	0.15	0.15	0.15

2.2 PLAXIS Numerical Modelling Procedures

A three-dimensional approach using PLAXIS 3D was employed to model the complete geometry of a shallow circular footing. Triangular elements were used to model the soil materials, allowing fourth-order interpolation for displacement calculations. Plate elements were used for the shallow footing and anchor plate, while the anchor rod was modelled with node-to-node elements. Standard boundary conditions were assumed, with full fixity applied at the base (horizontal displacement "v" and vertical displacement "u" set to zero) and roller conditions (u=0, v=0) applied to the vertical sides.

The expansive and non-expansive clay layers were represented using the hardening soil (HS) model, which was assumed to behave undrained under undrained analysis. In contrast, the granular pile sand was modelled using the Mohr-Coulomb (MC) approach, assuming drained behaviour. The Mohr-Coulomb model was selected as the most suitable for sandy soils after conducting trials and sensitivity analyses, which indicated that the hardening soil model was not appropriate. The anchor plate, anchor rod, and shallow footing were modelled as linear elastic materials, with their flexural rigidity set high enough to prevent unwanted buckling or deformation.

Swelling in the expansive soil layer was simulated by applying a 6.6% positive volumetric strain, derived from free swelling behaviour observed in a consolidation test. The volumetric strain values were specified along the x-, y-, and z-directions, where positive values indicate expansion and negative values indicate shrinkage. Under actual conditions, the rate of swelling in expansive clay typically varies with distance from the moisture source and overburden pressure. However, for simplicity in this analysis, the volumetric strain was applied uniformly across the entire thickness of the expansive soil layer, as illustrated in Fig. 3.

The net uplift force for the GPA was calculated by restricting the relative movement between the anchor plate and footing. When expansive, unsaturated soil begins to absorb water, it swells, producing an uplift force in the expansive soil layer, as shown in Fig. 4. This swelling causes the footing to rise due to volumetric changes, creating tension in the anchor. The tension force in the anchor represents the GPA's ultimate pull-out load resistance. This

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pull-out load is calculated at a reference point at the GPA head by determining the stress between nodes along the anchor.

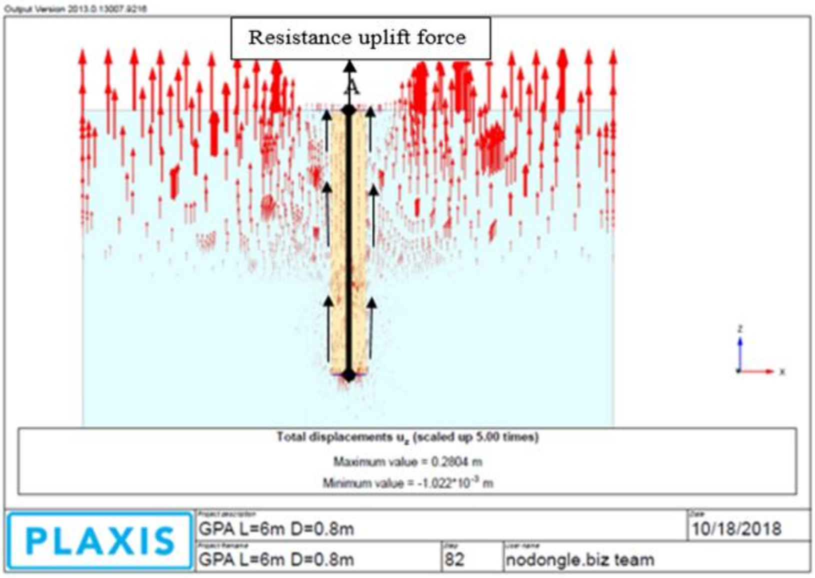

Fig. 3 *Volumetric strain was uniformly applied across the entire thickness of the expansive soil layer*

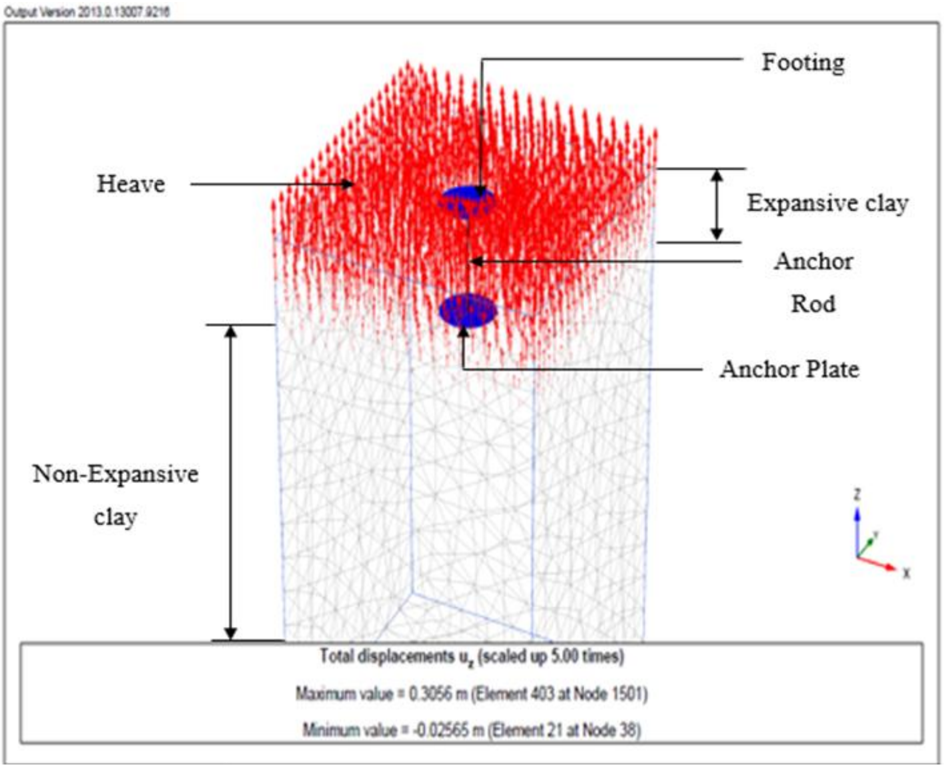

Fig. 4 *Expansive, unsaturated soil begins to absorb water, swelling occurs and produces an uplift force in the expansive soil layer*

3. Result and Analysis

The numerical modelling outcomes were derived using the PLAXIS software. Heave and uplift force measurements are recorded at each stage, and the process continues until the GPA fails. These readings are taken with respect to the upward displacement and forces observed in the shallow foundation. A detailed analysis reveals the heave and uplift force behaviour of the shallow footing, including GPA. Fig. 5 indicates how the heave of the shallow footing behaves with an increasing ratio of the length of GPA to the thickness of expansive soil (L/H) parameter.

This is also compared with an increasing number of anchor rod piles (N) using the same anchor plate diameter of 0.4 m. The results show that overall, an increase in L/H and the total number of anchor piles reduces the heave on the foundation. However, for a single anchor pile, the significance of the L/H parameter in reducing heave was only minor. A major decrease in heave values is observed when more than 1 anchor pile is used, but the difference between 2 and 4 anchor piles was not significant. Similar observations were also seen with the uplift pressure on the foundation. Fig. 6 shows that as L/H and the number of anchor piles (N) increase, the uplift pressure decreases. However, L/H = 1 shows slightly lower uplift pressure due to minor inconsistencies.

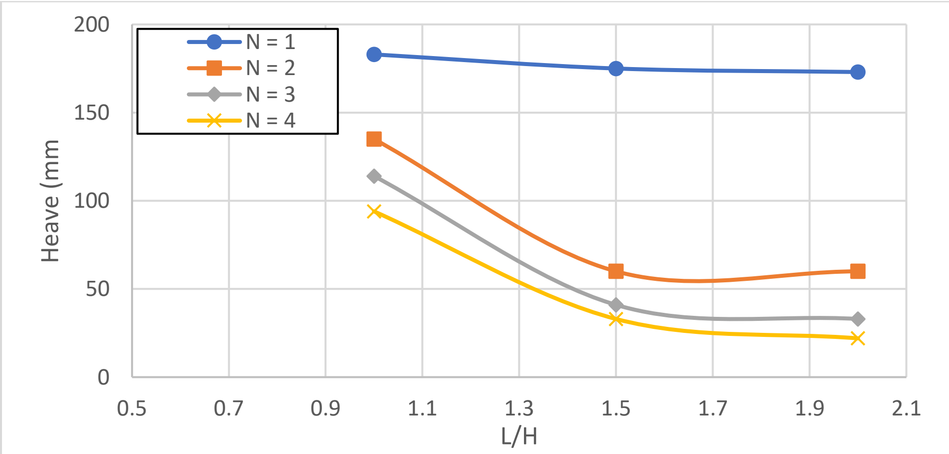

Fig. 5 *Heave behaviour with L/H parameter*

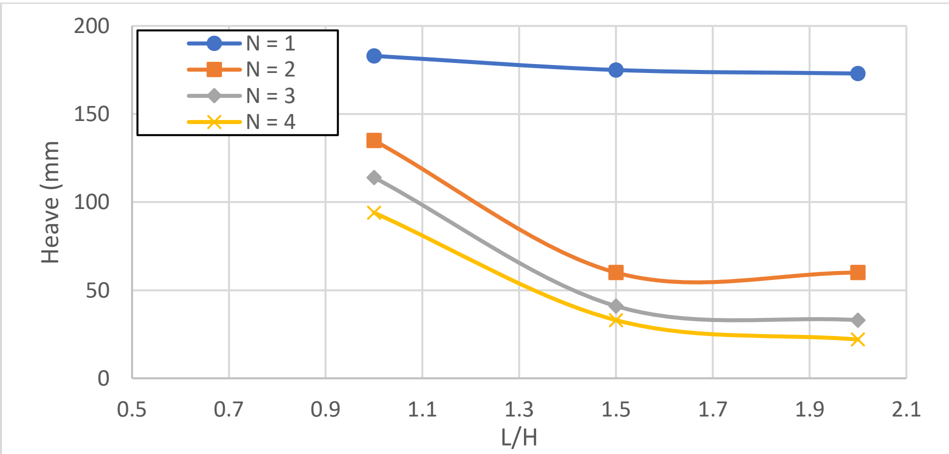

Fig. 6 *Uplift force behaviour with L/H parameter*

Another indication of the improvement effect on heave and uplift forces is the area replacement ratio (Ar), defined as the ratio of the foundation footing area to the cross-sectional area of the GPA anchor plates. The area replacement ratio (Ar) reflects the relative significance of the anchor plate area compared to the footing area in influencing heave and uplift forces. Fig. 7 indicates that a decrease in Ar would also decrease the overall heave. A further decrease in heave is observed as anchor pile length increases, but a significant change is only evident when comparing lengths of 4 meters and 6 meters. An increase in length from 6 meters to 8 meters yields only minor improvements. Also, the difference in the heave reading between 3 pile anchors and 4 pile anchors shows a minimum change. The behaviour of the group pile anchor, specifically 3 anchor piles with 6-meter lengths, shows performance similar to that of larger anchor plate diameters and anchor lengths. This shows an optimal design in terms of dimensions and the number of anchor piles, providing the minimum heave values. Fig. 8 confirms these findings, in which the area ratio (Ar) is compared with the uplift pressure. The GPA performance in terms of uplift pressure is optimal with 3 anchor piles and a length of 6 meters.

Table 4 presents the overall data on improvements in heave and uplift pressure across different dimensional input parameters. It can be seen that improvements of 82.55% in heave and 82.79% in uplift pressure are observed for group piles 3 and 6 meters in length. This shows significant improvement in reducing heaving in structures with an optimal design parameter: a group of granular pile anchors. All the results indicate that

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increasing the GPA's length and diameter reduces heave and uplift forces, aligning with observations from Phanikumar [21], Phanikumar et al. [22], Kumar et al. [23], Rao et al. [17], and Phanikumar et al. [24].

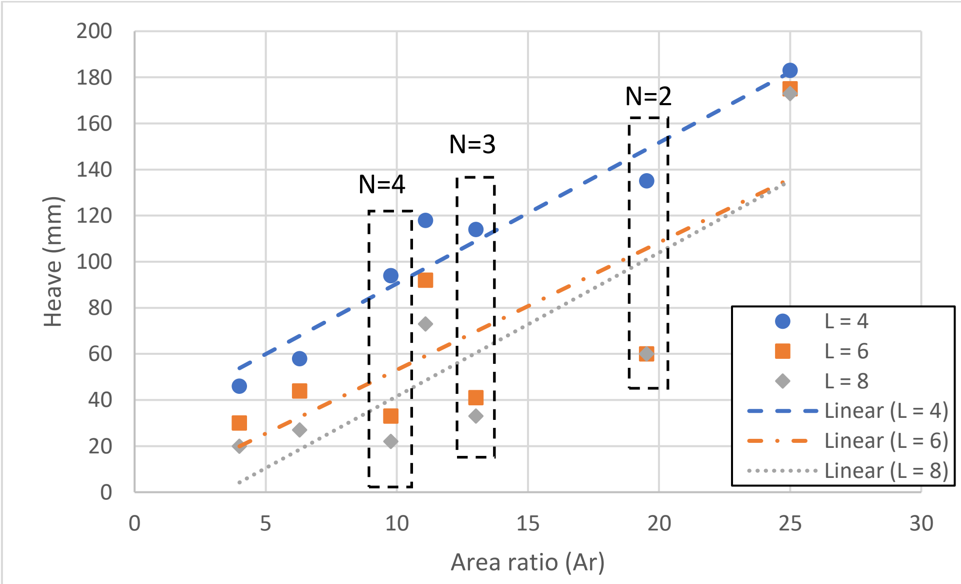

Fig. 7 *Heave behaviour with area ratio parameter*

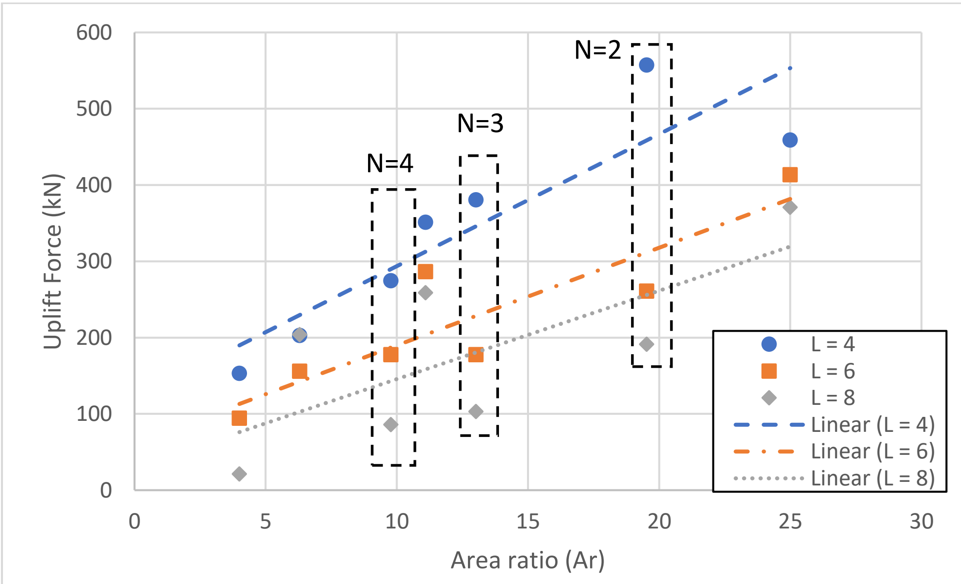

Fig. 8 *Uplift result behaviour with area ratio parameter*

Table 4 *Summary of the data from the test*

Diameter, D (m)	Length, L (m)	L/H	N	Ar	Heave improvement (%)	Swelling uplift force improvement (%)
Footing rests on clay with a diameter (d_1 = 2 m)					-	-
0.4	2	0.50	1	25.0	17.02	31.34
	4	1.00		25.0	36.60	36.90
	6	1.50		25.0	64.26	63.79
	8	2.00		25.0	71.49	71.44
0.6	2	0.50		11.1	22.13	35.80
	4	1.00		11.1	49.79	50.88
	6	1.50		11.1	75.32	71.62
	8	2.00		11.1	80.43	78.57
0.8	2	0.50		6.3	25.53	42.13
	4	1.00		6.3	60.85	59.89
	6	1.50		6.3	81.28	78.17
	8	2.00		6.3	87.23	86.78
1	2	0.50		4.0	26.38	48.11
	4	1.00		4.0	68.94	70.32
	6	1.50		4.0	88.51	86.14
	8	2.00		4.0	91.49	96.99
Footing rests on clay with a diameter (d_2 = 2.5 m)					-	-
0.4	4	1	2	19.53	42.55	46.07
	4	1	3	13.02	51.49	63.16
	4	1	4	9.77	60.00	73.42
	6	1.5	2	19.53	74.47	74.75
	6	1.5	3	13.02	82.55	82.79
	6	1.5	4	9.77	85.96	91.35
	8	2	2	19.53	74.47	81.50
	8	2	3	13.02	85.96	90.02
	8	2	4	9.77	90.64	91.68

4. Conclusion

In conclusion, this research offers a detailed examination of the use of granular pile anchor (GPA) systems to prevent shallow-foundation failures on expansive clay soils. The study builds on an innovative design approach that optimises granular pile anchors by accounting for various design parameters, such as the diameter and length of the anchor plate and rod in a GPA system. This approach enhances foundation sustainability by reducing repair and remediation associated with soil heaving, providing a practical solution for issues with shrinking and expansive soils.

The research outcomes propose an optimised design strategy that improves the efficiency of GPA systems, ensuring maximum stability through best-practice design methods. Overall findings are indicated as follows:

- Increasing the GPA's length and diameter reduces heave and uplift forces.
- These studies suggest that the swelling uplift force on the GPA results from the self-weight of the granular pile, which includes granular material, steel anchorage, and plates, as well as friction mobilised along the interface between the granular material and expansive soil, and lateral pressure from surrounding soil.
- Additionally, lateral swelling pressure from the surrounding expansive soil radially confines the GPA, reducing heaving.

The key outcome of this research is the identification of optimised design parameters, such as the L/H, Ar, and the number of anchor piles for the GPA system, which can serve as valuable guidelines for constructing improved shallow foundations in expansive soil conditions. Overall, this research significantly advances sustainable foundation design by providing practical solutions to real-world problems, promoting efficiency and sustainability in construction practices.

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Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Alvin John Lim Meng Siang;* ***Data collection:*** *Ehab Hamad Sfoog;* ***Analysis and interpretation of results:*** *Ehab Hamad Sfoog, Alvin John Lim Meng Siang;* ***Draft manuscript preparation:*** *Alvin John Lim Meng Siang, Nickholas Anting Anak Guntor, and Mohd. Hidayat Rabon. All authors reviewed the results and approved the final version of the manuscript.*

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