INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

IJIE

Vol. 16 No. 4 (2024) 204-213
https://publisher.uthm.edu.my/ojs/index.php/ijie

Optimum Sustainable Design Approach of a Granular Pile Anchor System in Mitigating Shallow Foundation Failures on Expansive Clay

Alvin John Lim Meng Siang[1]*, Ehab Hamad Sfoog[2], Sim Sy Yi[3], Nickholas Anting Anak Guntor[2], Faisal bin Sheikh Khalid[2], Mohd Hidayat Rabon[4]

[1] *Research Centre for Soft Soils, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*
[2] *Big Data and Advance Analytics Research, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*
[3] *Department of Electrical Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*
[4] *Muda Consult Sdn Bhd, 81200 Johor Bahru, Johor, MALAYSIA*

*Corresponding Author: alvin@uthm.edu.my

DOI: https://doi.org/10.30880/ijie.2024.16.04.024

Article Info

Received: 15 May 2024
Accepted: 10 August 2024
Available online: 27 October 2024

Keywords

Granular pile anchor, shallow foundation, expansive and shrinking soil

Abstract

Expansive soil is known for its capacity to undergo substantial volume fluctuations, expanding upon water absorption, and contracting during the drying process thus having profound problems for infrastructures, specifically for shallow foundations, which then requires periodic maintenance and repair works. This ultimately highlights the importance of a sustainable design approach to avoid unwanted consequences. Therefore, this research will be the forefront in addressing this issue by utilizing granular pile anchors (GPA) with various design alternatives to mitigate the heaving and swelling forces induced by expansive soil. This is achieved through numerical modelling analysis using the advanced 3D finite element software, PLAXIS which is focused in examining an optimal foundation structure design of GPA aimed at mitigating heave. The results showed that with the addition of GPA, there was a potential reduction of heave and to the uplift force on the foundation structure. The magnitude of the improvements was found to be controlled by three main independent design parameters of GPA which are the ratio of the GPA length to its diameter (L/D), the ratio of GPA length to the expansive soil layer thickness (L/H), and the area replacement ratio (Ar) which is the ratio of the foundation footing area to GPA cross section area. The largest improvement encountered compared to unreinforced shallow foundation was found to be using a design parameter of L/H = 2 and Ar = 4.0 where there was a 91.5% and 96.99% reduction in heave and uplift pressure respectively. Therefore, a shallow foundation can be constructed with the addition of GPA incorporating the optimum design parameters to maximise stability.

1. Introduction

Foundation is one of the key elements for sustainable building construction. There are certain cases where foundations are constructed on unfavourable soil conditions such as expansive soils. Expansive soils are widespread, and their adverse effects can be particularly pronounced in arid regions when subjected to wetting and drying cycles [1]. These soils, characterized by their propensity to swell when exposed to moisture and shrink when it dries, can wreak havoc on structures, causing foundation instability, structural damage, and financial losses [2]-[5]. Nonetheless, expansive soil is considered among the most sensitive types of soils which require special design for structural foundations to be built on.

Addressing the issues associated with expansive soils is a pressing concern in the construction industry. There already has been many approaches that was proposed and applied to minimise the destruction produced by expansive soils such as pre-wetting [6], drying-wetting cycle [7], chemical treatment [8]-[10] and soil reinforcement [11]. However, these proposed techniques to counter the heave of expansive soil may not eliminate the difficulty experienced in expansive soil completely, may not be practical, or may cause other issues on the other hand.

Alternatively, traditional mitigation strategies often involve costly foundation designs, such as deep piling or expansive soil moisture control, which may not always be economically or environmentally feasible. Even granular piles (stone columns) known for improving bearing capacity do not have the ability to counter the uplift force caused by the expansive soils since it is a mere particulate body that cannot resist tensile forces. In light of these challenges, an innovative solution has emerged which is the use of granular pile anchors (GPA) to counteract the detrimental effects of expansive soils.

Granular pile anchors (GPA) are a geotechnical technique that combines the principles of soil stabilization and foundation support to provide an effective, sustainable, and cost-efficient solution to expansive soil-related problems. This technique involves driving piles made of granular materials, typically sand or gravel, deep into the ground to serve as anchors for the foundation structure. The essential benefits of using granular pile anchors are ultimately to address expansive soil issues that includes enhancing stability and reducing ground movements.

Although there have been numerous research investigations done to examine the resistance of GPA, specifically by subjecting it to external pullout forces such as studies from Johnson and Sandeep [12], O'Kelly et al. [13], Sivakumar et al. [14], Sharma et al. [15], Rao et al. [16], Kranthikumar et al. [17], Izzati [18], Ganasan et. al. [19], and Buswig et. al. [20], none has established proper design parameters for an optimum sustainable design.

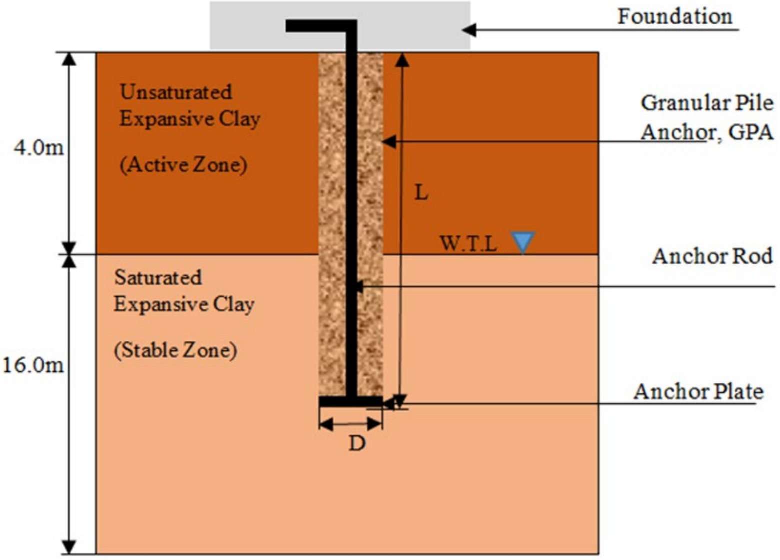

Fig. 1 *The granular pile anchor model diagram*

Therefore, this research is dedicated to the analysis of an optimal foundation structure design for GPA with the goal of mitigating heaving. This is accomplished via numerical modelling analysis employing the advanced 3D finite element software, PLAXIS. The optimum design of the GPA is studied by investigating different parameters in designing the GPA such as the length (L) and diameter (D) of the anchor as well as the thickness (H) of the expansive clay layer (active zone). The analysis of the GPA performance is measured by three main independent design parameters of GPA which are the ratio of the GPA length to its diameter (L/D), the ratio of GPA length to the expansive soil layer thickness (L/H), and the area replacement ration (Ar) which is the ratio of the foundation footing area to GPA cross section area. The simulated model of the GPA system which was extended from the shallow foundation is shown in Fig. 1. The active zone is reserved for unsaturated expansive clay soils and this depth varies based on conditions and locations. The optimum design parameters will be determined from this research and will be a good reference and guideline for an effective sustainable shallow foundation design structure specifically to reduce maintenance and repair works due to heaving.

2. Methodology

The method of experimentation design and analysis is explained to understand the materials and procedures used for the research.

2.1 Materials used for Analysis

The expansive soil materials that were used for the analysis of this study were identified as expansive clay and was taken from a construction site at Musyyb Babil province in Iraq. The location of the soil sampling was well known for its high potential expansion and shrinkage properties. The samples were collected from depths ranging between 0.5 to 2 meters under the original ground surface, which is from the unsaturated soil layer throughout the arid dry season. The samples were then sent to a laboratory for testing, to determine essential expansive clay parameters required as input for numerical modelling analysis. For the case of this research, the thickness (H) of the expansive clay layer is modelled to be 4 meters which is considered to be the active zone underlain by a non-expansive clay layer (stable zone) of 16 meters as shown in Fig. 2. Typical sand parameters were used as the modelling input values for the granular pile materials which is to provide support for the anchor system as seen in Fig. 1. The summary of all the input parameters is as indicated in Table 1. With addition to that, the materials used for the shallow footing, anchor system (plate and rod) are assumed to be steel, and its material properties will adopt typical rigid steel parameters as summarised in Table 2.

Fig. 2 *The granular pile anchor model diagram*

Table 1 *Summary of all the input parameters*

Model Parameters	Expansive Clay Un-drained Behaviour	Granular Pile Sand Drained Behaviour
Ɣunsat (kN/m^3)	16.33	17
Ɣsat (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
(ϕ́)$^\circ$	22	42
Volumetric strain% (swelling)	6.6	-
νu	-	0.25

Table 2 *Summary of steel properties used to simulate 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

The design of the experimental testing in this study involves a strategic set of granular pile anchor (GPA) dimensions. This is to ensure a variety in the results indicating the reaction of the foundation with GPA to heaving and uplift forces. Table 3 shows the summary of the GPA dimension and design parameters. It should be noted that the unreinforced footing is set with a dimension of 2 meters in diameter. The pile anchor which is connected from the unreinforced footing is extended with lengths that vary from less and beyond the expansive clay (active zone) depth.

Table 3 *Summary of the GPA dimension and design parameters*

(GPA) Diameter, D (m)	(GPA) Length, L (m)	Depth of Expansive Clay, H (m)	Area replacement ratio, Ar	L/D	L/H
Footing Diameter Resting on Unreinforced Expansive Soil (2 m)					
0.40	2.00	4.00	25.00	5.00	0.50
0.60			11.11	3.33	0.50
0.80			6.25	2.50	0.50
1.00			4.00	2.00	0.50
0.40	4.00		25.00	10.00	1.00
0.60			11.11	6.67	1.00
0.80			6.25	5.00	1.00
1.00			4.00	4.00	1.00
0.40	6.00		25.00	15.00	1.50
0.60			11.11	10.00	1.50
0.80			6.25	7.50	1.50
1.00			4.00	6.00	1.50
0.40	8.00		25.00	20.00	2.00
0.60			11.11	13.33	2.00
0.80			6.25	10.00	2.00
1.00			4.00	8.00	2.00

2.2 PLAXIS Numerical Modelling Procedures

A three-dimension method using PLAXIS 3D was used to model the full geometry of a shallow circular footing. The soil materials were modelled using triangular elements which provide a fourth order interpolation for displacement. The shallow footing and anchor plate were modelled using plate elements and the anchor rod was modelled using the node-to-node element. The boundary conditions were assumed using standard fixity. This means a full fixity at the base of the geometry (horizontal displacement "v" and vertical displacement "u" are zero) and roller conditions at the vertical sides (u= 0 and v= 0) were used.

The expansive and non-expansive clay layers were modelled using the hardening soil (HS) model and was assumed to behave in un-drained manner under method (A) of un-drained analysis. The granular pile sand in turn is modelled using the Mohr Coulomb (MC) method where it is assumed to behave in a drained manner. The Mohr-Coulomb model is selected as it is the most suitable for sandy soils as multiple trails and sensitivity analysis were conducted with the hardening soil model were deemed unsuitable. The rigid steel anchor plate, anchor rod and shallow footing was modelled as linear elastic model. The flexural rigidity of anchor plate, anchor rod, and footing assumed as very high to avoid unnecessary buckling and deformation.

The simulation of swelling in expansive soil layer was done by applying a positive volumetric strain of 6.6% to the expansive clay. A value which was referred from the free swelling behaviour in a consolidation test. The values of volumetric strain can be defined in three strain components of x, y and z directions. The positive value of the volumetric strain component represents and expansion, whereas the negative value represents shrinkage in that direction. In real conditions, the rate at which expansive clay would normally swell depends on the location from the source of moisture and magnitude of overburden pressure. However, for simplifying the analyses presented here in this research, the volumetric strain was applied uniformly across the full thickness of the expansive soil layer as shown in Fig. 3.

The net uplift force of the GPA in addition were determined by fixing the movement between the anchor plate and footing. When the expansive unsaturated soil starts absorbing water, swell will be generated and produces an uplift force in the expansive soil as show in Fig. 4. When this occurs, the footing will rise due to volumetric changes in will cause a tension force in the anchor. The value of tension force in the anchor is considered as the ultimate pull-out load resistance of GPA. The pull-out load is calculated at the reference point located at the GPA head by means of calculating the stress from node to node of the anchor. Therefore, the uplift force on the footing in any GPA can be determine using Eq. (1).

$$\mathrm{FP} = \mathrm{FS} - \mathrm{FR} \tag{1}$$

where FP = Net uplift force on the footing with GPA, FS = Uplift force in expansive soil without GPA, and FR = Resistance uplift force of GPA.

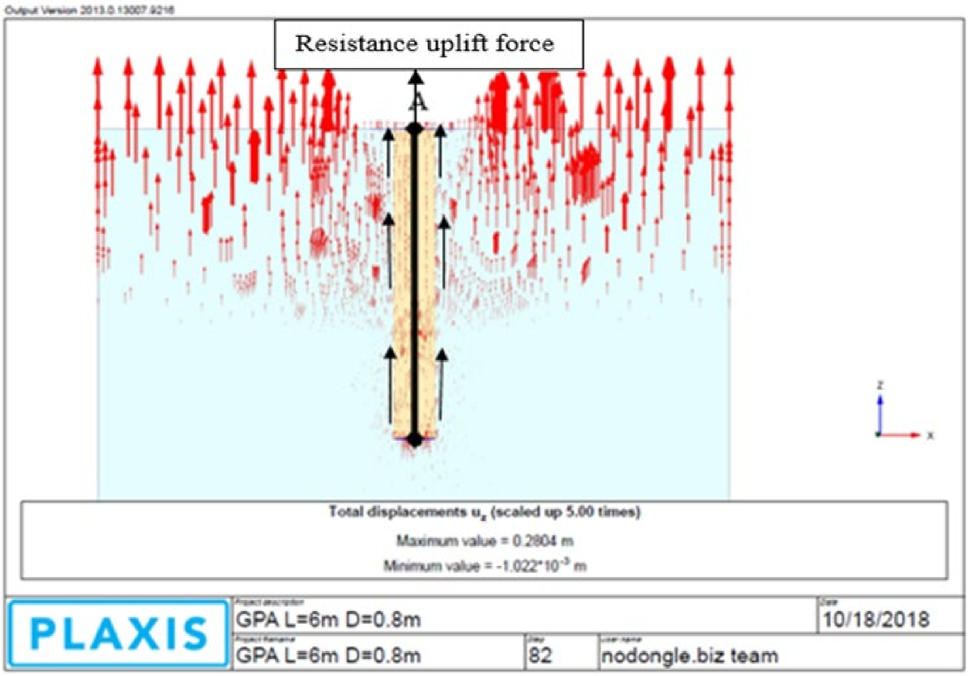

Fig. 3 *Volumetric distribution resulting to heave using PLAXIS 3D*

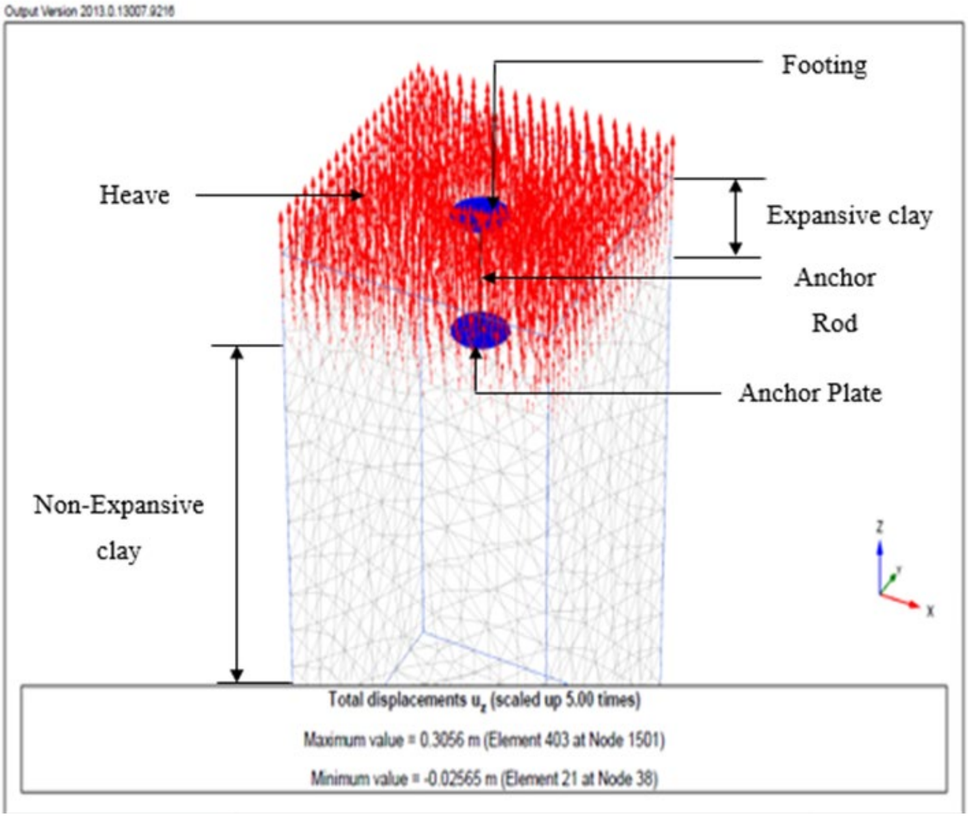

Fig. 4 *Shading diagram of the vertical displacement (m) due to uplift force response for anchor embedded in expansive clay*

3. Results and Analysis

The numerical modelling results were obtained from the PLAXIS software. The heave and the uplift force are recorded incrementally, and this progression persists until the GPA ultimately fails. The readings are recorded with reference to the upward displacement and forces detected on the shallow foundation. Detail analysis indicates heave and uplift force behaviour of the shallow footing with the incorporation of GPA. Fig. 5 indicates how the heave of the shallow footing behaves with increasing ratio of length of GPA to the thickness of expansive soil (L/H) parameter with different diameters of the anchor plate. It can be seen that an increase in the L/H parameters and the diameter of the anchor plate tends to lower the heaving of the footing. However, it can be seen that only the anchor plates that are larger than 0.4 m in diameter will have significant impact on heave reduction with increasing L/H parameter. This also goes to show the effects on the uplift forces on the footing. Fig. 6 indicates the reaction of the uplift forces with increasing L/H parameter with various anchor plate diameters. It can be seen that the uplift forces of the footing decrease significantly with increasing L/H and diameter of the anchor plates.

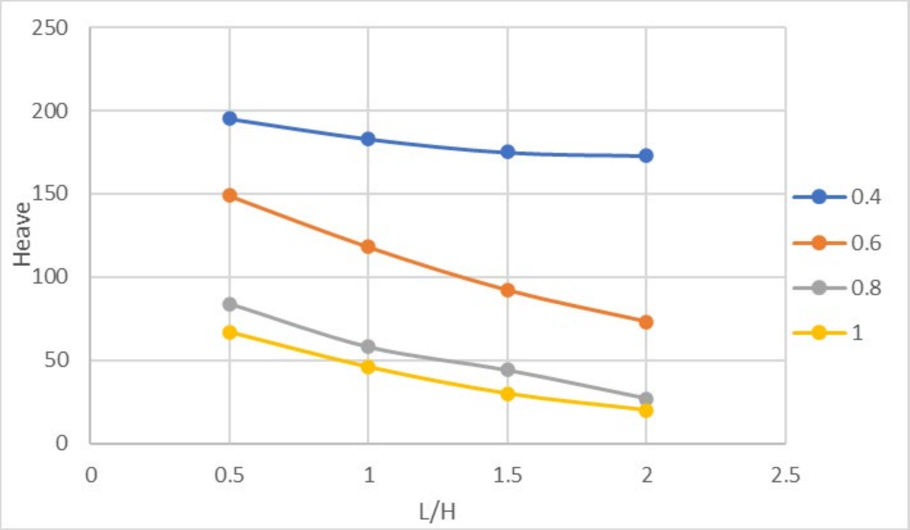

Fig. 5 *Results of heave behaviour with increasing L/H parameter with various anchor plate diameters*

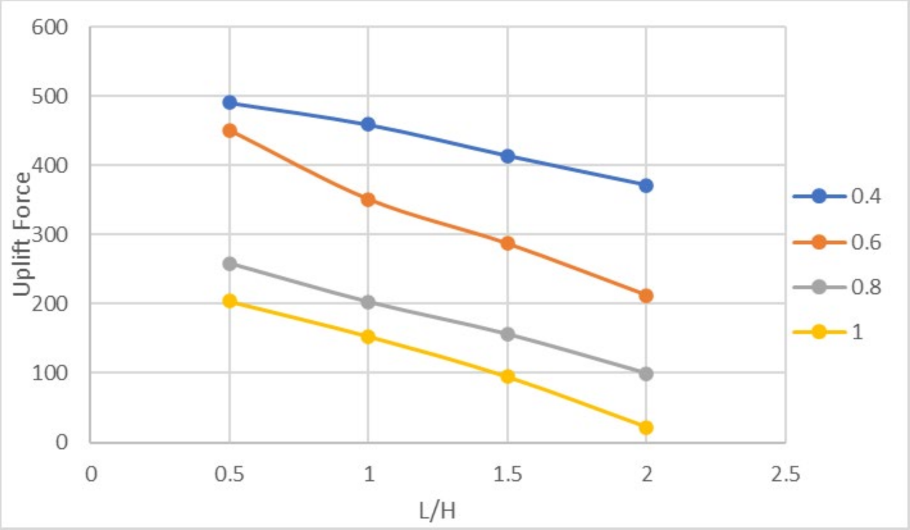

Fig. 6 *Results of the uplift forces with increasing L/H parameter with various anchor plate diameters*

The results of the ratio of the GPA length to its diameter (L/D) parameter also showed significant reaction on the heave and uplift forces. It can be seen in Fig. 7 and Fig. 8 that an increase in L/D parameter decreases the heave and uplift forces respectively. The results, however in fact indicate a wide scatter of readings throughout the plot, but there is a reasonable pattern can be seen of an overall decrease in the heave and uplift pressure when there is a change in the L/D parameter. Based on the results, the larger the value of L/D, the lower the heave and uplift forces encountered on the foundation. This also goes to show that longer GPA lengths provide more significant reactions in reducing heave and uplift forces as compared to GPA anchor plate diameters.

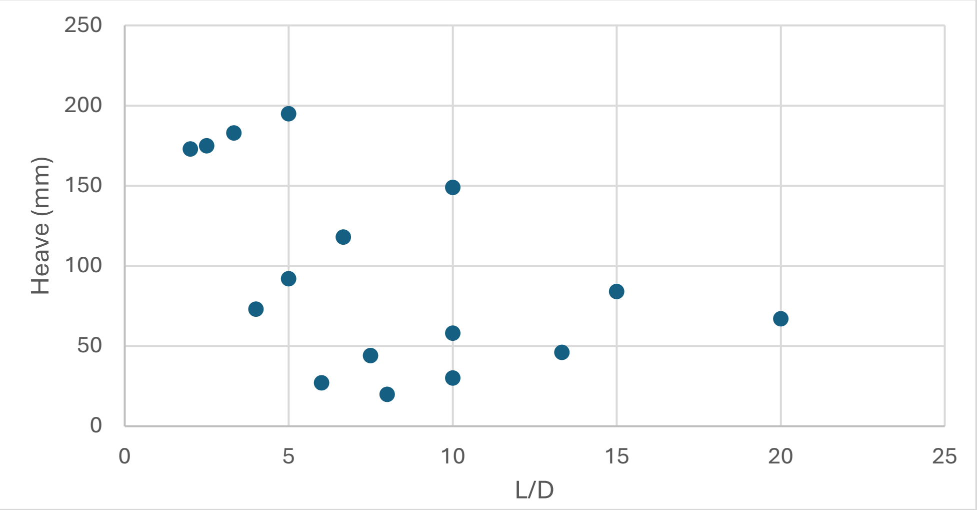

Fig. 7 *Reactions of L/D parameters on heave*

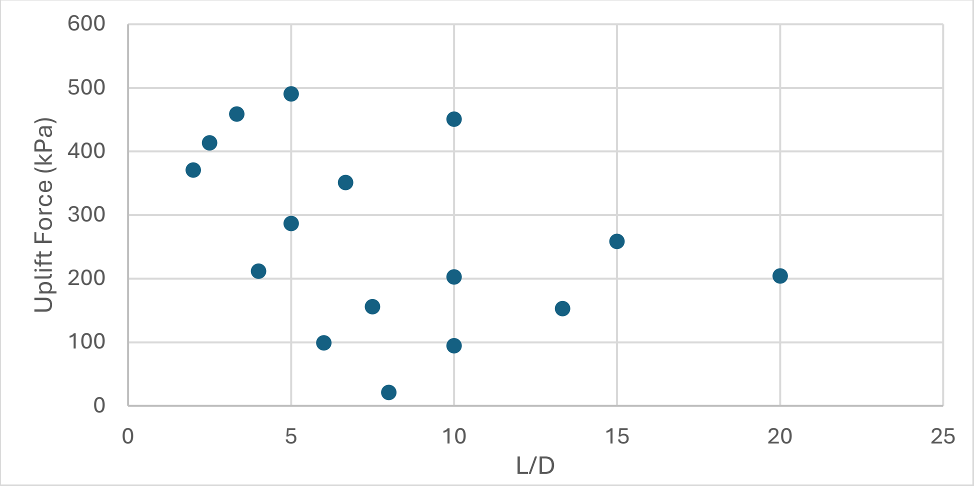

Fig. 8 *Reactions of L/D parameters on uplift forces*

Another indication on the effect of improvement in the heave and uplift force is through the area replacement ratio (Ar) which is the ratio of the foundation footing area to GPA anchor plates cross section area. The Ar indicates how significant the area of the anchor plates as compared to the area of the footing can play an important role in affecting heave and uplift forces. Fig. 9 indicates that heave decreases as Ar decreases. This indicates that as the area of the anchor plates get closer to the area of the shallow footing, there will be a significant decrease in heave. This is similar to what has been obtained in the results of the uplift force results where the uplift force decreases as the Ar decreases as seen in Fig. 10. The reason of this behaviour can be understood as when the footing diameter increases with constant GPA diameter, the area of the footing on which the swelling pressure acts is increased, resulting in an increment in the heave of the GPA foundation system.

Table 4 summarised the overall results of all the GPA design parameters with how much heave and uplift forces improvements that were obtained from the numerical modelling analysis as compared to that of the unreinforced shallow footing. It was found that the maximum heave and uplift force that was obtained from footing rest on un-reinforcement expansive clay with diameter (2m) are 235 mm and 715 kN respectively. It can be seen that there is a significant reduction of heave and uplift force when GPA has parameter of Ar = 4.0 and L/H = 2.0 and L/D = 8.0 where the values are 91.49% and 96.99% respectively. This shows that, for a given Ar ratio, the heave and uplift force decreases when L/H and L/D increases due to an increase in the GPA length. A significant reduction in heave was observed when GPA is penetrated in non-expansive clay layer at sufficient length. This means that the GPA can penetrate the non-expansive soil layer (stable zone) to provide a sufficient anchorage in the base of GPA to help for detaining the heave. This behaviour can be attributed due to the increase in the shear resistance in circumference of the penetrated length of the GPA.

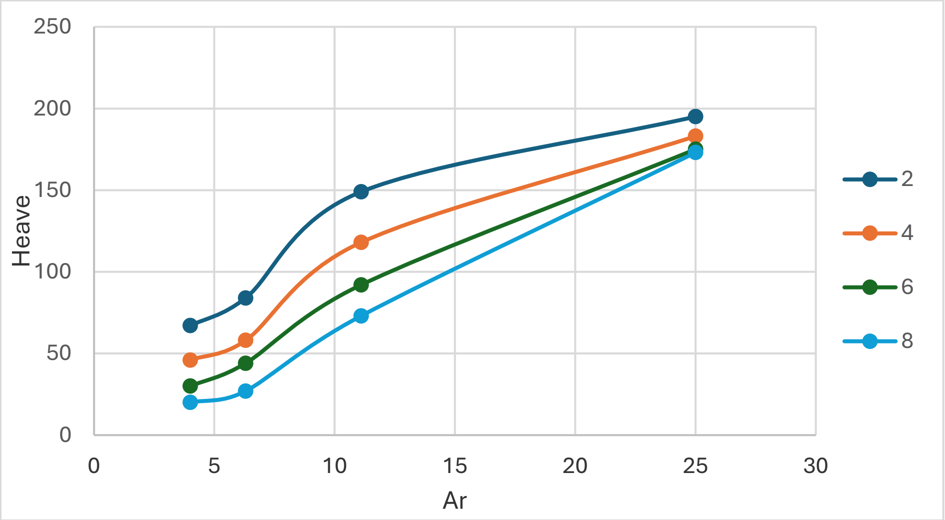

Fig. 9 *Heave behaviour measured with the area replacement ratio Ar and various GPA length*

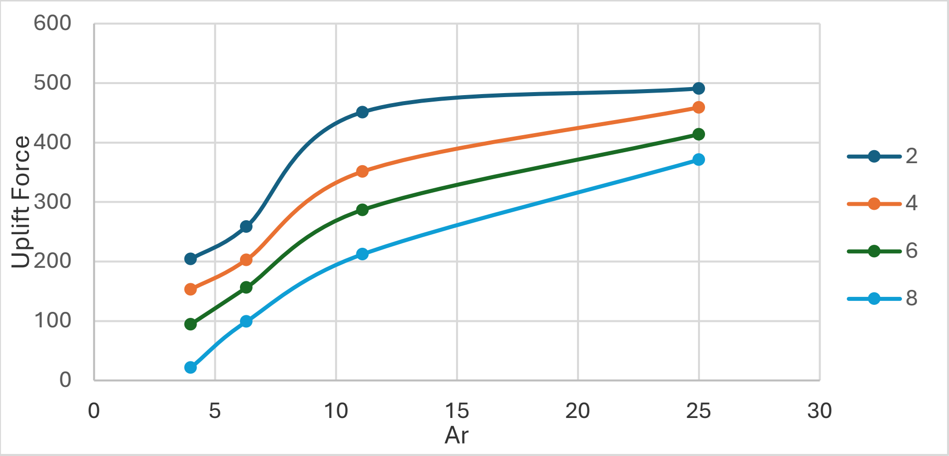

Fig. 10 *Uplift forces measurements with the area replacement ratio Ar and various GPA length*

Table 4 *Heave and uplift force improvement for different (L/H) and Ar*

Diameter, D (m)	Length, L (m)	L/D	L/H	Ar	Max. Heave (mm)	Uplift Force (kN)	Heave Improvement (%)	Swelling Uplift Force Improvement (%)
0.4	2	5.00	0.50	25.0	195	490.9	17.02	31.34
	4	3.33	1.00	25.0	183	459.0	36.60	36.90
	6	2.50	1.50	25.0	175	413.8	64.26	63.79
	8	2.00	2.00	25.0	173	371.0	71.49	71.44
0.6	2	10.00	0.50	11.1	149	451.2	22.13	35.80
	4	6.67	1.00	11.1	118	351.2	49.79	50.88
	6	5.00	1.50	11.1	92	286.8	75.32	71.62
	8	4.00	2.00	11.1	73	212.2	80.43	78.57
0.8	2	15.00	0.50	6.3	84	258.9	25.53	42.13
	4	10.00	1.00	6.3	58	202.9	60.85	59.89
	6	7.50	1.50	6.3	44	156.1	81.28	78.17
	8	6.00	2.00	6.3	27	99.1	87.23	86.78
1	2	20.00	0.50	4.0	67	204.2	26.38	48.11

4	13.33	1.00	4.0	46	153.2	68.94	70.32
6	10.00	1.50	4.0	30	94.5	88.51	86.14
8	8.00	2.00	4.0	20	21.5	91.49	96.99

4. Conclusion

As a conclusion, this research provides a comprehensive study on the use of granular pile anchor system to prevent failures in shallow foundations built on expansive clay soils. The study extends the findings of an innovative design approach that optimizes the use of granular pile anchors, with the consideration of a variety of design parameters such as the diameter and length of the anchor plate and rod respectively in a GPA system. This approach ensures the sustainability of the foundation system by minimizing repair and remediation works caused by heaving of the soil. This provides a better solution for a practical significance as it can solve problems under shrinking and expansive soils.

The outcome from this research can provide an optimized design approach that enhances the efficiency of granular pile anchor systems, ensuring maximum stability with the best design methods to be adopted. As an overall, it can be clearly observed that heave and uplift forces were reduced by increasing the GPA length and diameter. According to Phanikumar [21], Phanikumar et al. [22], Kumar et al. [23], Rao et al. [24]. Phanikumar et al. [25], the reason on the occurrence of this behavior is that the swelling uplift force acting on the GPA can be due to the self-weight of the granular pile which consists of the granular material, steel anchorage and steel plates. It is also due to the friction mobilized along the pile soil interface between the granular material and the expansive soil and the lateral pressure caused by the self-weight of the soil surrounding the GPA. Furthermore, the lateral swelling pressure caused by the surrounding expansive soil which confines the GPA radially producing a significant reaction to reduce heaving.

Therefore, the main outcome from this research is that an optimised design parameter of looking at the L/D, L/H and Ar of the GPA system can be an ultimate guideline for the construction of an improved shallow foundation design with GPA mainly to mitigate failures due to expansive soil conditions. Overall, the research contributes significantly to advancing knowledge and practice in sustainable foundation design. It offers practical solutions to real-world problems while promoting sustainability and efficiency in construction practices.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through Tier 1 (Vot Q353).

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the 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, Sim Sy Yi, Nickholas Anting Anak Guntor, Faisal bin Sheikh Khalid, Mohd. Hidayat Rabon. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Ng, C. W. W., & Menzies, B. (2014). Advanced Unsaturated Soil Mechanics and Engineering. CRC Press. https://doi.org/10.1201/9781482266122

[2] Steinberg, M. (2000). Expansive soils and the geomembrane remedy. Advances in Unsaturated Geotechnics, pp. 456-466. https://doi.org/10.1061/40510(287)31

[3] Abiodun, A. A., & Nalbantoglu, Z. (2015). Lime pile techniques for the improvement of clay soils. Canadian Geotechnical Journal, 52(6), 760-768. https://doi.org/10.1139/cgj-2014-0073

[4] Siang, A. J. L. M., Wijeyesekera D. C., Lim, S. M., & Zainorabidin, A. (2012). Innovative laboratory assessment of the resilient behaviour of materials (rigid, elastic and particulates). Procedia Engineering, 53, 156-166. https://doi.org/10.1016/j.proeng.2013.02.021

[5] Siang, A. J. L. M., Wijeyesekera D. C., Lim, & Zainorabidin, A. (2013). The effect of particle morphology of sand on the relationship between shear strength and dilatancy characteristics. Electronic Journal of Geotechnical Engineering, 18H, 1537 – 1546.

[6] Nelson, J., & Miller, D. J. (1997). Expansive Soils: Problem and Practice in Foundation and Pavement Engineering. John Wiley & Sons.

[7] Soltani, A., Deng, A., Taheri, A., & Mirzababaei, M. (2018). Rubber powder–polymer combined stabilization of South Australian expansive soils. Geosynthetics International, 25(3), 304-321. https://doi.org/10.1680/jgein.18.00009

[8] Zhao, H., Ge, L., Petry, T. M., & Sun, Y. Z. (2014). Effects of chemical stabilizers on an expansive clay. KSCE Journal of Civil Engineering, 18(4), 1009-1017. https://doi.org/10.1007/s12205-013-1014-5

[9] Tran, T. D., Cui, Y. J., Tang, A. M., Audiguier, M., & Cojean, R. (2014). Effects of lime treatment on the microstructure and hydraulic conductivity of Héricourt clay. Journal of Rock Mechanics and Geotechnical Engineering, 6(5), 399-404. https://doi.org/10.1016/j.jrmge.2014.07.001

[10] Dafalla, M., Al-Shamrani, M., & Al-Mahbashi, A. (2017). Expansive Soil foundation practice in a semiarid region. Journal of Performance of Constructed Facilities, 31(5), 0401-7084. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001078

[11] Hejazi, S. M., Sheikhzadeh, M., Abtahi, S. M., & Zadhoush, A. (2012). A simple review of soil reinforcement by using natural and synthetic fibers. Construction and building materials, 30, 100-116. https://doi.org/10.1016/j.conbuildmat.2011.11.045

[12] Johnson, N., & Sandeep, M. N. (2016). Ground Improvement Using Granular Pile Anchor Foundation. Procedia Technology, 24, 263–270. https://doi.org/10.1016/j.protcy.2016.05.035

[13] O'Kelly, B. C., Brinkgreve, R. B. J., & Sivakumar, V. (2014). Pullout resistance of granular anchors in clay for undrained condition. Soils and Foundations, 54(6), 1145–1158. https://doi.org/10.1016/j.sandf.2014.11.009

[14] Sivakumar, V., O'Kelly, B. C., Madhav, M. R., Moorhead, C., & Rankin, B. (2012). Granular anchors under vertical loading – axial pull. Canadian Geotechnical Journal, 50(2), 123–132. https://doi.org/10.1139/cgj-2012-0203

[15] Sharma, A., & Sharma, R. K. (2019). An experimental study on uplift behaviour of granular anchor pile in stabilized expansive soil. International Journal of Geotechnical Engineering, 15(8), 1–14. https://doi.org/10.1080/19386362.2019.1597481

[16] Rao, A. S., Phanikumar, B. R., Babu, R. D., & Suresh, K. (2007). Pullout behavior of granular pile-anchors in expansive clay beds in situ. Journal of Geotechnical and Geoenvironmental Engineering, 133(5), 531–538. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:5(531)

[17] Kranthikumar, A., Sawant, V. A., Kumar, P., & Shukla, S. K. (2017). Numerical and experimental investigations of granular anchor piles in loose sandy soil subjected to uplift loading. International Journal of Geomechanics, 17(2), 04016059. https://doi.org/10.1061/(ASCE)GM.1943-5622.0000733

[18] Izzati, P. N. F., Ismail, B., Lim, A. J. N. S., & Herman, S. (2017). Stability of peat soil by using envirotac. Matec Web of Conferences, 103(5), 07014. https://doi.org/10.1051/matecconf/201710307014

[19] Ganasan, R., Lim, A. J. M. S., & Wijeyesekera, D. C. (2016). Physical and software modelling for challenging soil structure interaction. ARPN Journal of Engineering and Applied Sciences, 11(6), 3668-3676.

[20] Buswig, Y. M., Othman, A., Julai, N., Sim, S. Y., Utomo, W. M., & Lim, A. J. M. S. (2018). Voltage tracking of a multi-input interleaved buck-boost DC-DC converter using artificial neural network control. Journal of Telecommunication, Electronic and Computer Engineering, 10, 29-32.

[21] Phanikumar, B. R. (1997). A Study of Swelling Characteristics of Granular Pile-Anchor Foundation System in Expansive Soils. JNTU. https://doi.org/10.1007/s40098-016-0180-z

[22] Phanikumar, B. R., R.S., S., Srirama, R. ., & Madhav, M. R. (2004). Granular Pile-anchor foundation (GPAF) system for improving engineering properties of expansive clay beds. Geotechnical Testing Journal, 27(3), 279–287. https://doi.org/10.1080/17486025.2014.985336

[23] Kumar, P., Kumar, M., Chandaluri, V. K., & Sawant, V. A. (2018). Uplift capacity of single and group of granular anchor pile system. Journal of Civil Engineering, Science and Technology, 9(1), 34–40.

[24] Rao, A. S., Phanikumar, B. R., Babu, R. D., & Suresh, K. (2007). Pullout behavior of granular pile-anchors in expansive clay beds in situ. Journal of Geotechnical and Geoenvironmental Engineering, 133(5), 531–538.

[25] Phanikumar, B. R., Rao, A. S., & Suresh, K. (2008). Field Behavior of granular pile anchors in expansive soils. Proceedings of the Institution of Civil Engineers-Ground Improvement, pp. 199–206.