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# Optimum Design of Granular Pile Anchor System for Ground Improvement on Expansive and Shrinking Soil

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**ABSTRACT**

Expansive and shrinking soil that exist in various regions worldwide, has a significant disadvantage due to its expanding and shrinking properties and the repetition process of this phenomenon will cause fatigue and distress to structures resulting in cracks. To reinforce these expansive soils, an innovative technique called the Granular Pile Anchor (GPA) system is used that offers tensile strength, counteracting the forces in an upward direction and minimizing heave. Limitation to prior studies is that it only focuses on load-displacement relationships using the pull-out technique, where an external force is applied to the GPA, and the resulting displacements are measured. These results indicate the GPA's capability to withstand the force being exerted. However, this is not the case in real conditions, heave and expansion forces occur due to water absorption, which exerts pressure and pushes the entire soil bed upward, including the GPA. Therefore, this paper aims to investigate this concept through physical experiments from a small-scale model and numerical studies consisting of a single pile with varying diameters and lengths to determine its optimum design. The reinforced soil ultimately demonstrates a reduction in upward the force and vertical movement in contrast to unreinforced soil. Furthermore, the tests confirm that there is an almost linear relationship between the upward force and heave in both the experimental and numerical investigations. Consequently, incorporating a GPA system into shallow foundations proves to effectively mitigate heave and shrinkage issues in expansive soils, thereby addressing construction-related challenges.

## 1. Introduction

Expansive soils, which are found in many areas of the world pose a significant threat to the foundations of lightly loaded structures, particularly in semi-arid and arid regions where wetting and drying cycles intensify their damaging effects. [1]. Expansive soil is generally clay soil which can be

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recognised due to their high plasticity, excessive heave behaviour, and has high potential of swelling and shrinking [2-4]. Huge economic losses occur as a result of significant damages to structures for instance road pavement, pedestrian sidewalks, lightweight structures and buildings that are constructed on soil prone to movements, mainly due to the repeated occurrences of this phenomenon. Numerous approaches were proposed and applied to minimise the destruction produced by expansive soils such as pre-wetting [5], drying-wetting cycles [6], chemical treatment [7-9], and soil reinforcement [10]. 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.

Granular piles (stone columns), that are used for improving the bearing capacity and decreasing the settlements of soft soil layers, are considered one of the high potential techniques used for ground improvement. However, the granular pile does 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. Therefore, Phanikumar [11] proposed joining the foundation above the granular pile to a steel plate through a steel anchor rod, and thus the granular pile transform in becoming a tension-resistant granular pile-anchor foundation, GPA, that can resist the uplift force of expansive soil imposed on the structure due to soil swelling. Within the context of GPA (Granular Pile Anchor), the foundation experiences an uplift force vertically as a result of the heave pressure exerted by the expansive soil. However, this uplift force is balanced by the downward force generated by the weight of the granular pile and the friction occurring at the interface between the pile and the soil. This friction force is created by the presence of an anchor within the granular pile, which strengthens as the lateral swelling pressure increases. As a result, the foundation uplift is effectively prevented.

Numerous research investigations have been done to examine the resistance of GPA, specifically by subjecting it to external pullout forces. Examples of such studies include those conducted by 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], Norazam *et al.,* [18], Ganasan [19], and Buswig [20]. On the other hand, certain studies have focused on investigating the heave, shrinkage behavior and skin friction of expansive soil, such as the works of Ibrahim *et al.,* [21], Phanikumar [22], Phanikumar and Muthukumar [23], and Ismail and Shahin [24], Gunawan *et al.,* [25]. However, these studies primarily emphasized the application of external pullout forces and recording the corresponding displacement to evaluate GPA resistance, rather than considering the internal uplift force exerted by the expansive soil itself during the transition from unsaturation to saturation under heave impact. In reality, the heave and expansion forces arise due to the pressure resulting from water absorption, causing an upward displacement of the entire soil bed along with the GPA.

Therefore, this research is focused in investigating the aforementioned external forces due to soil pressure to simulate the working conditions on the granular pile anchor foundation and also evaluating its optimal design performance by comparing different rod diameters and lengths of the GPA system in a small-scale laboratory model and validated through numerical modelling.

## 2. Methodology

Experimental physical testing techniques were utilized using a small-scale model to explore the potential of the granular pile anchor in enhancing the stability of expansive soils, specifically in mitigating heave and uplift forces. A scaled length of the GPA of 20 cm and 40 cm was used to see significant improvements of the system. Then, these same conditions were simulated using numerical software of PLAXIS 3D adopting a non-linear elastoplastic model. Numerical modelling was used again to further simulate a larger range of GPA lengths and anchor plate diameter to show how effectively the GPA system works at real applications. The granular pile sand materials adopt the Mohr Coulomb (MC) model, whereas rigid steel properties were used for the anchor plate and rod. In order to simulate the swelling of expansive soil layer, a positive volumetric strain is applied to the expansive clay. Table 1 indicates the summary of the GPA dimensions for the physical and numerical modelling.

**Table 1**
Summary of the GPA dimensions

| Testing method | GPA length (m) | Anchor plate diameter (m) |
|---|---|---|
| Physical modelling and numerical modelling | 0.20<br>0.40 | 0.04 |
| Numerical modelling | 2 | 0.4, 0.6, 0.8, 1.0 |
| | 4 | 0.4, 0.6, 0.8, 1.0 |

### *2.1 Materials Utilised*

The soil investigated in this study was acquired from a construction site at Musyyb Babil province in Iraq which is well known for its high potential for expansion and shrinkage properties. This soil was intended for the construction of an affordable building. The soil 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. Index properties of this expansive soil are summarized in Table 2. It is evident that this particular soil type comprises a significant proportion of fine particles, with sand containing 7% of sand, while the residual content is distributed into clay of 51% and silt of 42%. Furthermore, the Atterberg limit test results revealed a liquid limit of 59% and a plastic limit of 23%, producing a 36% of plasticity index. Consequently, based on the category of the unified soil classification system (USCS), this soil type is graded as high plasticity soil (CH). Specifically, the specific gravity is 2.73, with the maximum unit weight of 16.3 kN/m3, and optimum moisture content, and initial void ratio of 21.5%, and 0.674, respectively. For the granular pile anchor (GPA), sand was utilized as a fill material, which falls under the poorly graded soil (SP) classification according to the USCS as summarized in Table 3. The intention behind using this type of sand is to impart frictional properties, enhancing the soil's resistance against expansion.

**Table 2**
Expansive soil index property

| Soil Property | Value |
|---|---|
| Specific Gravity ($G_s$) | 2.73 |
| Percentage of Liquid limit (LL) | 59 |
| Percentage of Plastic limit (PL) | 23 |
| Percentage of Plasticity Index (PI) | 36 |
| Percentage of Clay | 51 |
| Percentage of Gravel | 0 |
| Percentage of Sand | 7 |
| Percentage of Silt | 42 |
| Percentage of Organic Matter | 1.93 |
| Percentage of Gypsum Content | 1.85 |
| Percentage of Total Soluble Salts | 1.05 |
| Percentage of Sulphate (SO3) | 0.86 |
| Maximum Unit Weight ($\gamma_{dry}$), | 16.3 |
| Percentage of Optimum Moisture Content (OMC) | 21.5 |
| Initial Void Ratio ($e_o$) | 0.674 |
| Percentage of Montmorillonite | 48.3 |
| Percentage of Illite | 30.6 |
| Percentage of Kaolinite | 21.1 |
| Soil Classification (USCS) | CH |

**Table 3**
Index properties of the sand

| Property | Value |
|---|---|
| Specific Gravity ($G_s$) | 2.64 |
| $D_{10}$ | 0.179 |
| $D_{30}$ | 0.308 |
| $D_{60}$ | 0.5 |
| Uniformity Coefficient ($C_u$) | 2.793 |
| Coefficient of Curvature ($C_c$) | 1.06 |
| Max Unit Weight ($\gamma_{max}$), kN/m³ | 18.5 |
| Min Unit Weight ($\gamma_{min}$), kN/m³ | 14.10 |
| Relative Density (Dr)% | 72 |
| Unit Weight ($\gamma_{dry}$), kN/m³ | 17 |
| Percentage of Optimum Moisture Content (OMC)% | 12 |
| Max Void Ratio ($e_{max:}$) | 0.88 |
| Min Void Ratio ($e_{min:}$) | 0.437 |
| Void Ratio ($e_0$) | 0.564 |
| Cohesion (c), kPa | 3 |
| Friction Angle (Ø)° | 42 |
| Classification System (USCS) | SP |

## *2.2 Preparation of Samples*

The physical model for laboratory experimentation was constructed utilizing a container of stainless-steel materials, measuring with a length of 30 cm, a width of 30 cm, a height of 65 cm, and a thickness of 4 mm, as depicted in Figure 1. To simulate real site conditions, two primary layers were prepared in the model. The first layer, known as the stable zone, was completely saturated. A moisture content of 23.1% was identified in the expansive soil, resulting in a 94% degree of saturation. By gently compacting the soil, the soil layer reached a thickness of 35 cm. The second layer, representing the unsaturated soil or active zone, exhibited a degree of saturation of 70% and

18.3% moisture content, mirroring the dry season conditions on-site. Compaction was carried out until this soil layer achieved a level 25 cm of thickness. Preliminary testing was conducted to assess the physical properties of the soil to ascertain its appropriateness for the subsequent testing procedures.

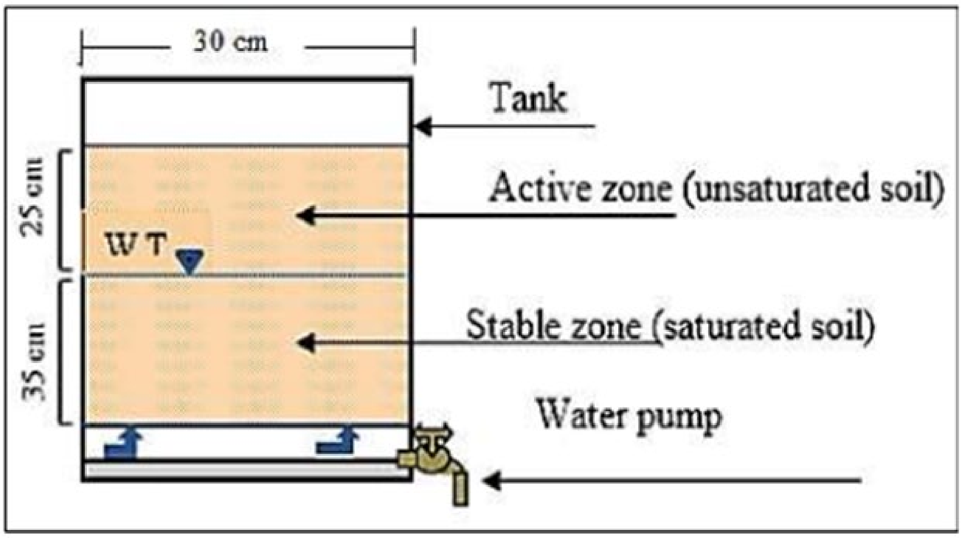


**Fig. 1**. Physical model for laboratory testing

*2.3 Installation Procedure for the Granular Pile Anchor (GPA)*

The setting up of the granular pile anchor (GPA) model was placed at the location of the soil bed midpoint of the expansive soil. It was then carefully from the surface; a PVC pipe was driven into it so that it penetrates up to the lowest level of the soil which is the soil bed to create a hole for the GPA. The GPA diameter is 4 cm, while the length is set varied between 20 cm and 40 cm. Subsequently, the plate on the base, accompanied by the anchor rod, was placed within the hole. The sand was then gently poured layer by layer and was tapped using a steel bar to make sure the area around the rod anchor is compacted, which was then altered within the interface of the expansive soil.

*2.4 Testing Method*

Figure 2 illustrates the experimental setup, consisting of the loading compression machine and the components of the reading and recording instrumentations. Initially, the heave test was conducted on the plain expansive soil with no GPA. Subsequently, the test was repeated with GPA. In each case, the soil bed was saturated by allowing water to flow through it until full saturation was achieved. The soil then proceeded to increase or expand under wetting until reaching a state of equilibrium with no further expansion.

To determine the pressure of the swelling, the sample was put under a loading pressure incrementally until it reached the initial stage of expansion. This test adhered to the guidelines performed on one-dimensional swelling or collapsing of cohesive soils (ASTM D4546-08). The purpose of this test was to find the ultimate uplift force, which corresponds to the force needed to return the height of the sample to its original condition before the occurrence of expansion happens. The numerical modelling was done with similar conditions and dimensions to that of the physical modelling as illustrated in Figure 3. It was then adjusted to real site dimensions to simulate different anchor lengths at site. Figures 4 and 5 show the output of the numerical modelling test showing how it depicts deformation and the reaction forces of the test respectively.

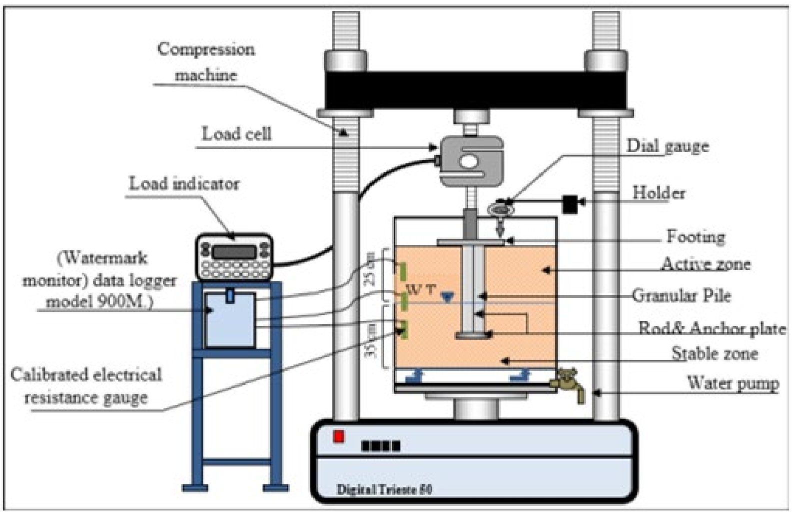


**Fig. 2.** The experimental setup of the physical test

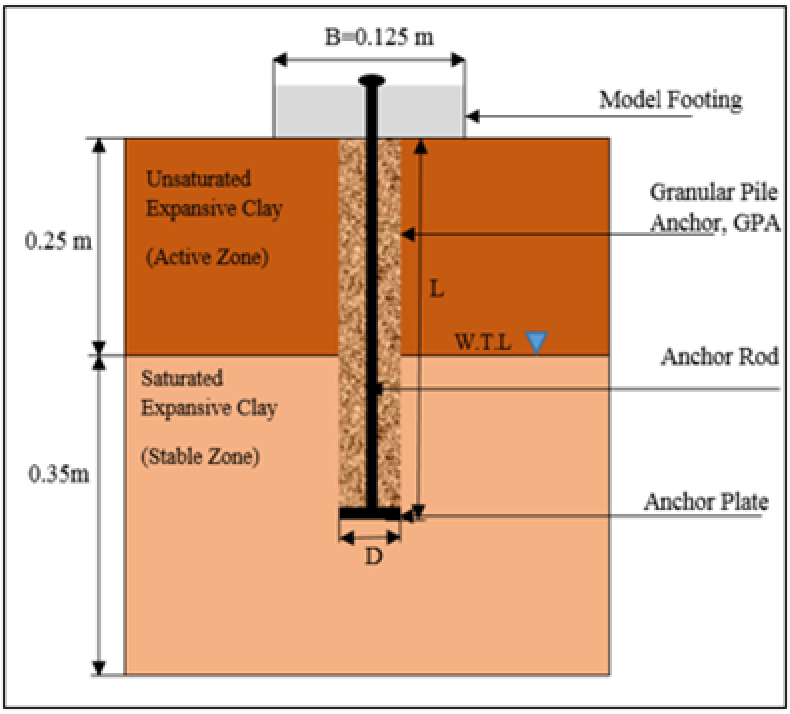


**Fig. 3.** The model details of the numerical modelling test

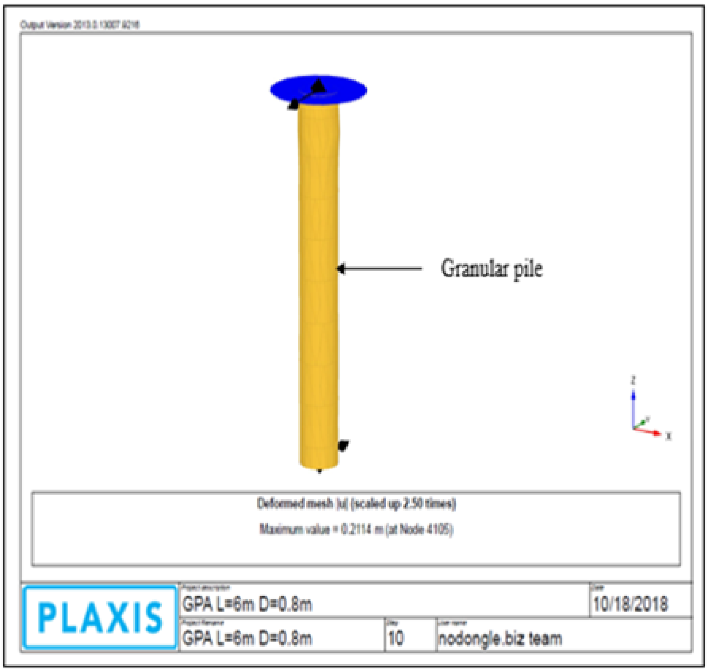


**Fig. 4.** Physical model for laboratory testing

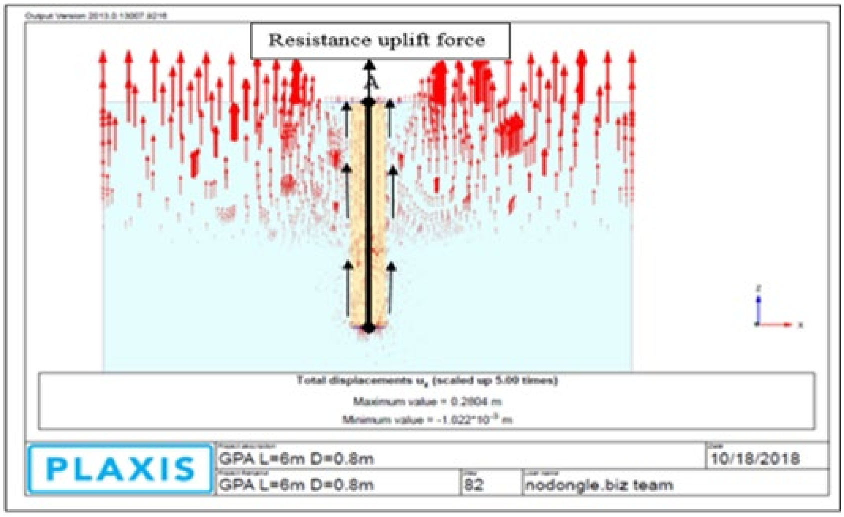


**Fig. 5.** Numerical model for laboratory testing

## 3. Results and Analysis

The results of the testing from the modelling require the soil sample to be simulated as close to site conditions. With that, the physical properties of the soil were first determined by doing initial testing from the odometer and proctor compaction test to make sure that the soil is as close to the required working conditions.

### *3.1 The Mechanical Properties of the Soil*

The expansive soil saturation level was examined at different levels of moisture and associated to the vane shear test results of shear strength. The expansive soil was prepared to attain a saturation level of 70%, which represents the saturation level observed on-site during the dry season. This saturation level is critical because it leads to maximum soil expansion when saturation reaches 94% which leads to a significant decrease in shear strength.

Table 4 presents the mechanical properties of the expansive soil. The soil shear strength was examined through drained conditions, utilizing consolidated drained triaxial tests with a velocity of 0.02 mm/min. The tests yielded a drained cohesion (c') of 30 kPa and an angle of internal friction (Ø’) of 22°. Additionally, for this specific type of soil the compression index (Cc) is 0.332. The behaviour of the soil of swelling and collapsing is depicted in Figure 6. In this study, the soil was permitted to swell to a maximum value of 6.6% from the total height of the sample. Subsequently, an application of incremental load was done to compact the soil and to ascertain the swell pressure. The pressure of the swelling, identified as 205 kPa, represents the pressure required to prevent further swelling.

**Table 4**
Properties of the expansive soil form mechanical testing

| Test | Soil properties | Values |
|---|---|---|
| Triaxial Test (Consolidated Drained) (CD at 0.02 mm/min) with adjusted | Drained Cohesion (c’), kPa | 30 |
| velocity | Drained Friction Angle, φ | 22 |
| One dimensional consolidation or swelling test | Swelling pressure (kPa) | 205 |
| | Compression Index (Cc) | 0.332 |
| | Free Swelling (%) | 6.6 |
| | Swelling Index (Cs) | 0.076 |

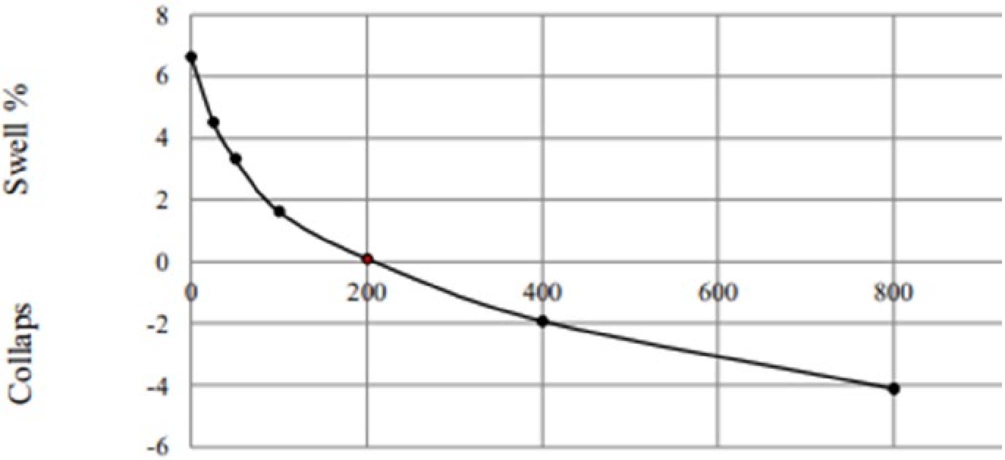


**Fig. 6.** The behaviour of swell and collapse of the soil

### *3.2 The Relationship of the Heave-Force Characteristics*

The investigation of the upward force arising from swelling pressure was carried out through both experimental and numerical approaches. Numerical investigation plays a vital role in this research, enabling a precise understanding of the outcomes. Typically, the upward displacement alongside incremental pull-out forces are carefully recorded, and this progression persists until the GPA ultimately fails. This method provides a sign, in the form of displacement records, regarding the resistance from the GPAs to the uplift force that was applied. However, it should be noted that this approach does not indicate the actual forces resulting from pore water pressure and the subsequent soil expansion over time.

In the present study, the investigation focused on exploring the resultant force generated within the expansive, resulting in heave. To induce heave in the physical testing, water was pumped at the model’s base, allowing the soil to reach a degree of saturation of 70%. The documented uplift force from the compression machine is the maximum uplift force that is considered, which is equivalent to the force required to compress the sample back to the height of its original condition.

The results obtained from both experimental testing of physical and numerical modeling is presented in Figures 7 and 8 respectively. Generally, the upward force and heave was reduced for the reinforced soil compared to the unreinforced soil. Table 5 offers a summary of the enhancements and the degree of resemblance, drawing a comparison between numerical simulations and physical experiments across all tests. The results unveiled a significant decrease in heave, with reinforced soil demonstrating up to a 50% reduction in heave as opposed to unreinforced soil. Additionally, the application of Geosynthetic Reinforced Soil (GPAs) effectively mitigated the upward forces, resulting in an approximate 60% reduction. The incorporation of a system with the existence of an anchor provided tensile force resistance caused by water absorption.

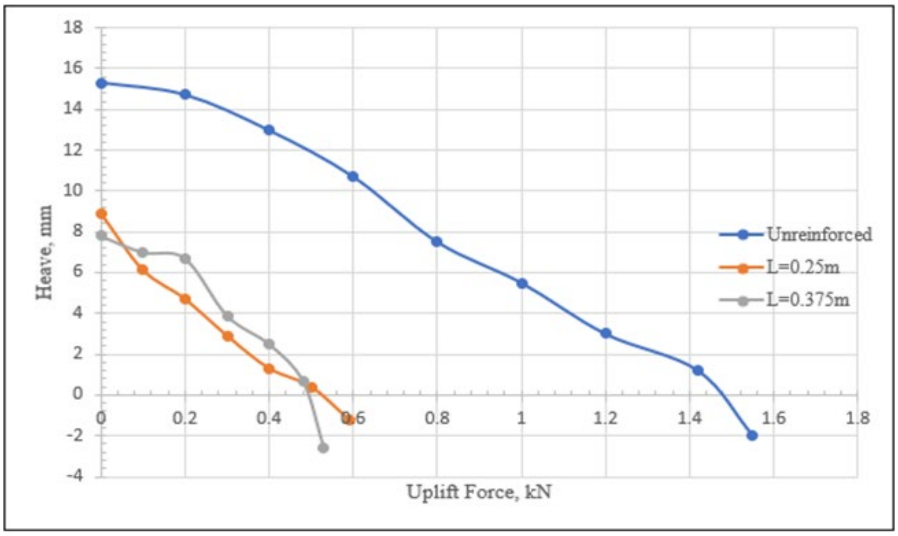


**Fig. 7.** The reaction on heave with uplift force for physical modelling

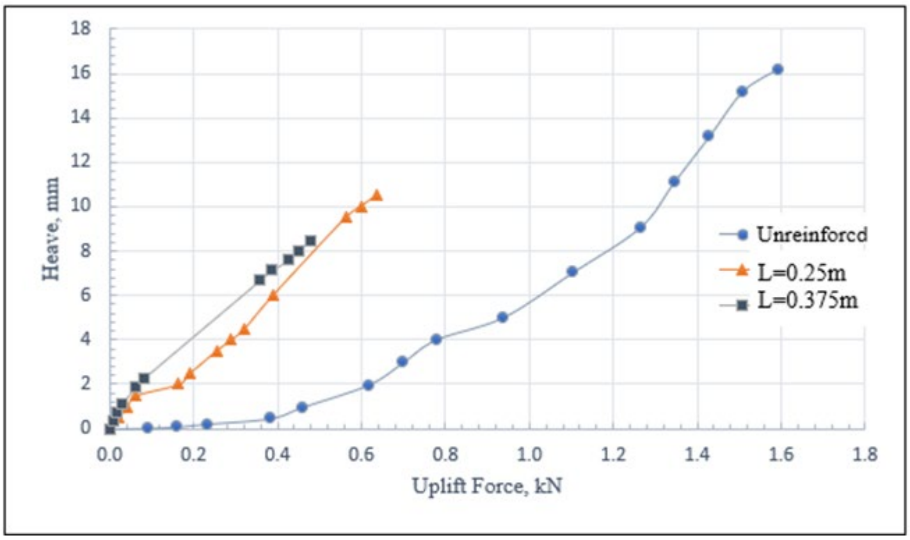


**Fig. 8.** The reaction on heave with uplift force for numerical modelling

**Table 5**
Comparison summary of the experimental and numerical outcomes

| L (m) | D (m) | Maximum Heave (mm) Experimental | Maximum Heave (mm) Numerical | Maximum Heave (mm) Similarity % | Maximum Uplift Force kN Experimental | Maximum Uplift Force kN Numerical | Maximum Uplift Force kN Similarity % | Degree of improvement (%) Experimental | Degree of improvement (%) Numerical |
|---|---|---|---|---|---|---|---|---|---|
| Unreinforced | | 15.3 | 16.2 | 94 | 1.47 | 1.59 | 98 | - | - |
| 0.20 | 0.04 | 8.9 | 10.5 | 85 | 0.55 | 0.64 | 86 | 42 | 35 |
| 0.40 | | 7.8 | 8.5 | 92 | 0.5 | 0.48 | 96 | 49 | 48 |

For the numerical modelling testing that extends the validity of the testing by incorporating real GPA lengths and diameters, it can be clearly observed that the uplift forces in GPA were reduced by increasing the GPA length and diameter. When the GPA length was 2 m, as shown in Figure 9, the heave and the corresponding uplift swelling force decreased as the diameter increased. Thus, as the contacting interface between the GPA and expansive soil gets bigger, the efficiency of the GPA becomes better which mainly caused in this case by the GPA self-weight and friction mobilised along the soil pile interface. For 2 m GPA length, the minimum value for heave was 17.02 % at lowest value of 0.4 m diameter. However, for the same length, as the diameter increased to 1 m, the heave significantly improved and obtained as 71.49 %. Also, when GPA length increased to 4m as shown in Figure 10, the minimum heave and maximum heave were 22.13 % and 80.43 % for 0.4 m and 1 m diameters respectively.

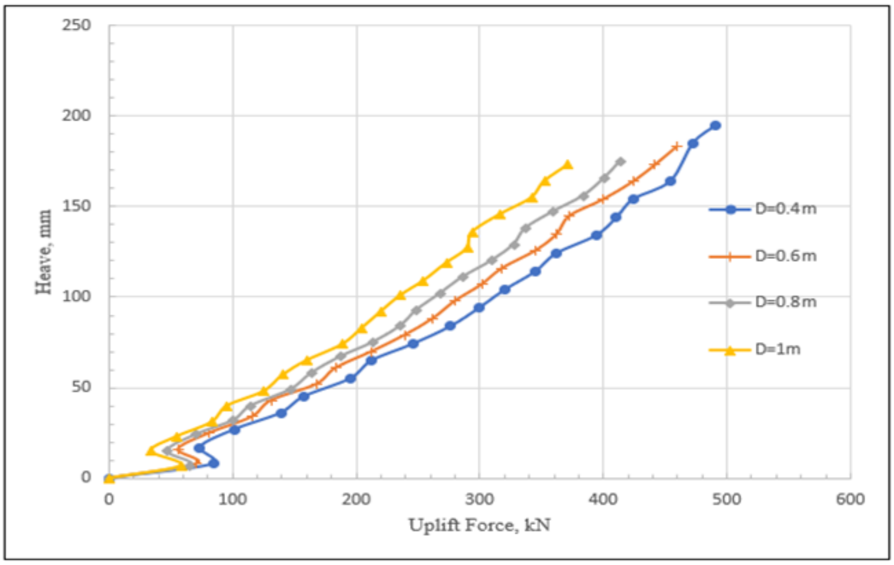


**Fig. 9.** The reaction of heave with increasing anchor diameter of 2m GPA length

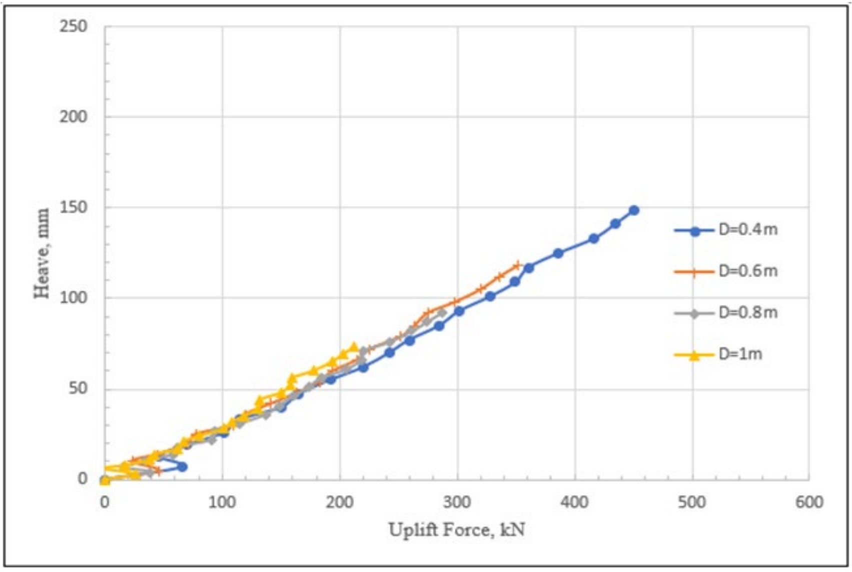


**Fig. 10.** The reaction of heave with increasing anchor diameter of 4m GPA length

## 4. Conclusions

This research paper presents the findings of a small-scale laboratory test conducted to examine the behaviour of Geosynthetic Anchor Piles (GAPs) in expansive soil. The obtained results were compared using PLAXIS 3D which is a finite-element analysis software. The GPA diameter was kept constant at 4 cm, while the lengths tested were 20 cm and 40 cm. The investigation focused on establishing the relationship between the net upward force and heave resulting from soil expansion.

The results indicate that there is an almost linear relationship between the upward force of the expansive soil and the corresponding heave. Moreover, the incorporation of GPA has a significant effect in reducing this force-heave relationship. The study reveals a maximum heave reduction of 50% in the reinforced soil as seen to that of the unreinforced soil. Furthermore, the application of GPAs effectively mitigates the upward forces, resulting in an approximate 60% reduction. Incorporating an anchor system offers the ability to counteract the tensile forces triggered by water absorption. The effectiveness identified in this study aligns with what was observed in the research conducted by Shanin and Ismail. [25].

The comparison between the experimental testing and numerical modelling for heave cases of unreinforced soil, 20 cm length GPA, and 40 cm length GPA have a similarity of 96.4%, 84.8%, and 93.2% respectively. Likewise, the similarity observed between the experimental and numerical outcomes concerning the upward force in unreinforced soil., 20 cm length GPA, and 40 cm length GPA, is 94.4%, 89.5%, and 87.2% respectively. Consequently, this study tries to accurately assess the effectiveness of GPA in reducing uplift forces and heave behaviour, which can potentially cause damage to structures. The technique employed in this research provides a direct representation of real site conditions during soil heave and shrinkage, where soil pressure is utilized to indicate and measure the uplift force of the pile, ensuring greater accuracy compared to previous studies that relied on pull-out forces.

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