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Measuring the Swelling Pressure and Heave of Expansive Soil Reinforced by Granular Pile Anchor Foundations

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Granular Pile Anchor (GPA) is one of the techniques used to overcome the geotechnical issues related to the volume change of the expansive soil. This study presents a technique that can be used to evaluate the performance of GPA in reducing the swelling pressure of expansive soil without applying any external uplift force. Finite element modelling was used to model the components of GPA and the surrounding expansive soil bed. The results were validated by conducting experimental tests in which the soil properties were similar to those considered for the numerical modelling. According to the findings, the outcomes from the physical and numerical models demonstrated a high level of agreement. It was concluded that the proposed technique is a reliable way to measure the heave and uplift pressure of the expansive soil as it depends on the volume change behaviour of the expansive soil itself without the need for applying equivalent external uplift force.

Keywords: expansive soil; swelling pressure; volume change; heave

I. INTRODUCTION

Expansive soil experiences volume change (swelling and shrinkage) upon changing the water content. Puppala *et al.* (2002) stated that the expansive soil mainly consists of kaolinite, montmorillonite, and illite group minerals. It is characterised by high differential settlement, high water absorbability, and low shear strength and bearing capacity (Kempfert & Gebreselassie, 2006). Therefore, it could be a major reason for severe structural damage.

Among the techniques that were proposed to overcome the geotechnical issues that arise due to the volume change of expansive soil, an efficient and cost-effective technique called Granular Pile Anchor (GPA) that was introduced by Phanikumar *et al.* (2004) to reduce the heave of expansive soil. GPA is a modification form of the conventional granular pile; anchorage was added to the granular pile to withstand the tension force generated by the swelling pressure of the heave.

GPA is mainly aimed at resisting the uplift pressure of expansive soil that develops due to changing the water content of expansive soil. The granular fill provides additional frictional resistance along the pile skin and reduces the uplift movement. The conventional granular pile might be useful to increase the bearing capacity of soil as it withstands compression loads. Therefore, adding an anchor is essential to enable the granular piles to overcome the uplift pressure of expansive soil. The top of the anchor must be strongly attached to the foundation to avoid pull-out failure (Rao *et al.*, 2007).

Several studies (Kranthikumar *et al.*, 2017; Sharma, 2019; Raghuram *et al.*, 2016; O'Kelly *et al.*, 2014; Kumar *et al.*, 2018) were presented to investigate the effectiveness and the factors affecting the performance of GPA. However, most of these studies considered applying an external pull-out load to simulate the swelling pressure rather than considering the uplift (swelling) pressure. On the other hand, the swelling

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*Corresponding author's e-mail: israa.j.alhani@buog.edu.iq pressure was experimentally measured by following several testing methods and techniques, including suction measurements, triaxial test, and oedometer test (Brackley, 1973; Abduljauwad & Al-Sulaimani, 1993; Al-Shamrani & Al-Mhaidib, 2000; Thompson *et al.*, 2006).

The oedometer test was the most frequently used method in measuring swelling pressure as it is a simple and straightforward test. According to Brackley 1973, three testing techniques by using the oedometer test were highlighted in measuring the swelling pressure. Later, Ali and Elturabi (1984) and Sridharan *et al.* (1986) found that the values of swelling pressure vary depending on the test methods listed by Brackley (1973). However, Soundara and Robinson (2009) explained the reason behind the variation in swelling pressure values, which was attributed to the changes in soil fabric after SEM tests.

This study introduced a new measuring technique of swelling pressure by using numerical modelling (Plaxis 3D). The tension force of the GPA rod, which resulted from the uplift pressure of expansive soil, was the key parameter to measure the swelling pressure.

II. RESEARCH METHODOLOGY

A. Preliminary Tests

Preliminary tests were conducted to measure the soil parameters considered inputs during the modelling phase. These tests included the Triaxial test and the Direct Shear test (to measure the mechanical parameters of the test materials), and the Oedometer test (to determine parameters such as Compression Index, Swelling Index, Free Swelling, and Swelling Pressure). Table 1 presents all parameters obtained from the preliminary tests.

Table 1. Soil Parameters obtained from the preliminary tests.

Model Parameters	**Expansive Clay**	**Granular Pile (Sand)**
γ_{unsat} (kN/m³)	14.95	18.3
γ_{sat} (kN/m³)	18.5	22.3
Volumetric strain %	6.56	-
Drain condition	Undrained	Drained
Compression Index (Cc)	0.34	-
Heaving Index	0.068	-
Uplift Pressure (kPa)	205	-
E (kN/m²)	-	68.5 x10³
E_{oed}^{ref} (kN/m²)	3090	-
E_{50} (kN/m²)	3460	-

The swelling pressure in this test was identified by applying load on the specimens after completing the swelling upon achieving full saturation condition. The load that caused the specimens to retrieve the original volume was taken as swelling pressure, as shown in Figure 1.

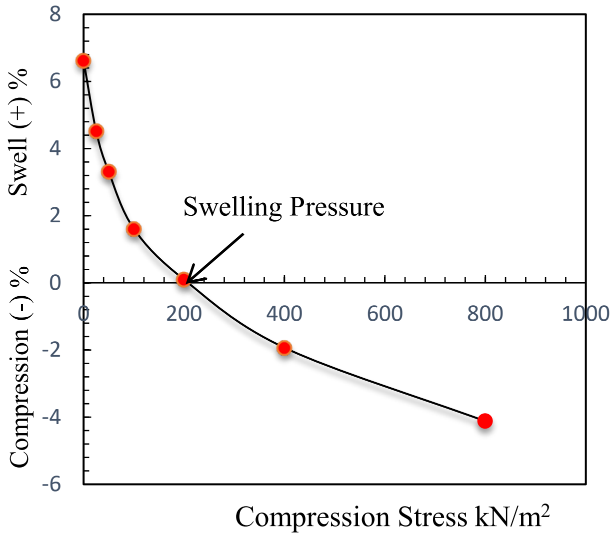

Figure 1. Oedometer data showing the swelling pressure of soil.

The technique of determining the uplift force of the soil followed in this study is consistent with Method (A) that Brackley (1973) highlighted. The results shown in Table 1 indicate serious volume change upon wetting the expansive soil. Notably, expansive soil's swelling behaviour is unique (Sfoog *et al.*, 2020). Other types of soil would exhibit either minor volume change or volume reduction behaviour, such as the inundation settlement that occurs upon saturation of soil (Albadri *et al.*, 2023; Lim *et al.*, 2022; Albadri *et al.*, 2021; Alhani *et al.*, 2022).

III. NUMERICAL MODELLING

The Finite Elements Method (FEM) was used by using PLAXIS 3D to model the swelling of expansive soil through applying positive volumetric strain to the soil model. The finite element equations for distortion theory, consolidation theory, and seepage theory, that were essential during the modelling process, are well defined and presented in PLAXIS Manual. Standard fixity is used to assume the boundary conditions. Which means the horizontal and vertical displacements are both zero.

The essential components of Granular Pile Anchored foundation (GPA) are the top foundation that connected to the underneath rod, then the rod that links the foundation above the ground level with the bottom plate, the filling material around the rod to increase the uplift resistance by the frictional resistance developing between the coarse filling material and the surrounding clay. And lastly, the bottom plate that works as platform for the whole foundation system. In this study, two rods' lengths were considered to evaluate the performance of GPA at different lengths.

The expansive and non-expansive soil (underneath the expansive soil) were modelled using the Hardening Soil (HS) model and assumed to behave in undrained conditions.

Anchor plates, anchor rods, and shallow footing are made of rigid steel, which is thought to be a linear elastic (LE) model. To prevent needless buckling and deformation, it is believed that the anchor plate, anchor rod, and footing have extremely high flexural stiffness. However, Mohr-Coulomb (MC) is used to represent the granular pile (sand). It was thought to act in a depleted state. Following several tests and sensitivity analysis, the hardening soil model and the Mohr-Coulomb model were chosen. Mohr-Coulomb model was selected as found straightforward, simple and easy to use as well as due to its proven reliability by several studies that focused on simulating the soil behaviour under different loading conditions (Doherty & Muir, 2013; Chen, 2022). During the simulating process, it was found that the mechanical parameters required for the expansive soil were effectively captured and it showed high accuracy for the modelling that involved multiple simulations (expansive soil and granular pile anchor).

The global medium option determines the number of triangular elements and the average element size. To enable more precise stress distribution, the medium setting is taken into consideration while creating the model's basic global finite element mesh. A patching test and several experiments with the various medium settings in 3D-PLAXIS were used to choose the medium mesh setting. For medium mesh, the relative element size factor of 1 was selected. Figure 2 shows the modelled GPA embedded in simulated expansive soil section at which the heave ranges are illustrated.

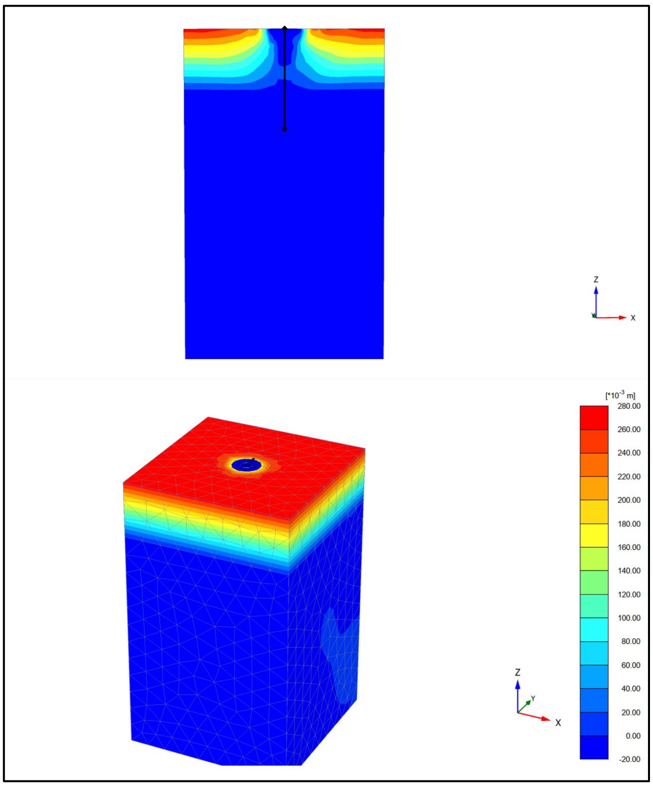

Figure 2. Side view and 3D diagram of GPA in a middle of expansive soil.

IV. TEST RESULTS

A. Results of Numerical Modelling

The expansive clay is subjected to a positive volumetric strain of 6.6% in order to simulate the expansion of the expansive soil layer. Using the Oedometer test, the free swelling test result for expansive soil yielded the same value.

The location of the moisture supply and the amount of overburden pressure determine how quickly expansive clay would normally swell. However, in order to reduce the complexity of the modelling process, the values of volumetric strain and swelling index were applied for the whole layer of the expansive soil. In these situations, the interface between the clay and sand layers at the GPA side will be utilized since R_{inter} = 0.97 (Brinkgreve *et al.*, 2013). Likewise, finite element computations were used to determine the heave, which was then referred to as the heave phase. At this stage, the expanded clay cluster's positive volumetric strains become active.

GPA is embedded in the expansive clay layer and subjected to swelling upon applying the positive volumetric strains on the expansive clay without loading activation. The footing will rise due to volumetric change in expansive clay and will cause tension force in the anchor produced from expansive heave since the base plate of GPA was modelled as a fixed end. The value of tension in the anchor is considered the GPA's uplift resistance force, calculated at the reference point located at the GPA head.

When the unsaturated soil starts absorbing the water, the heave will generate uplift force. The uplift force for any GPA can be found by the equation below

$$F_P = F_S - F_R$$

Where:

F_P = Net uplift pressure of GPA

F_S = Swelling pressure of expansive soil without GPA

F_R = Uplift resistance force of GPA

The above-mentioned method was utilised to determine the swell pressure of expansive soil after utilising GPA because there isn't a direct measuring tool for the uplift pressure of expansive soil. Using GPA derived from 3D-PLAXIS software, Figure 3 shows the heave behaviour and associated uplift forces for both unreinforced and reinforced soil. Also, Table 2 shows the values of heave and swelling pressure with and without GPA based on numerical modelling. The GPA-reinforced soil exhibited less heave and swelling pressure than nonreinforced soil.

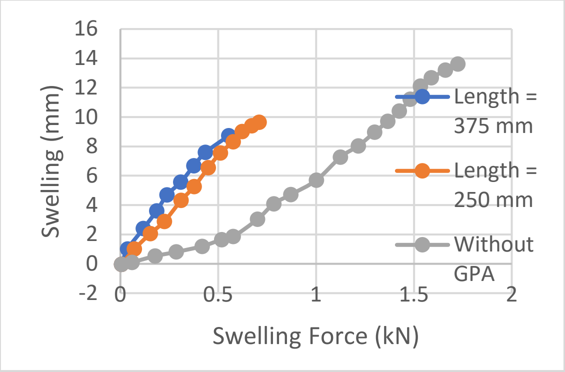

Figure 3. Heave behaviour of GPA-reinforced soil (with rod lengths of 375 mm and 250 mm) and unreinforced soil.

Table 2. Values of heave and swelling force of expansive soil obtained from numerical modelling.

Test Condition	**Heave (mm)**	**Swelling Force (kN)**
Expansive soil without GPA	16.2	1.59
Expansive soil with GPA L=250 mm	10.5	0.64
Expansive soil with GPA L=375 mm	8.5	0.48

B. Results Validation

Experimental tests were carried out to validate the results obtained from the numerical modelling. In this study, a small-scale GPA model with dimensions and material properties similar to those considered in the numerical modelling was subjected to loading by a loading machine. The dimensions of GPA used in the numerical modelling, and the physical were scaled down of 1/16 of an actual and full-scale GPA, this scale was considered as it agrees with the scale used by (Ibrahim *et al.*, 2014). Figure 4 shows the full setting of the small-scale physical GPA model.

A steel-made soil container, with dimensions of 350 mm length, 350 mm width and 700 mm height, was fabricated and equipped with a valve at the container's base to regulate the water flow during saturation. Both types of soil (expansive and non-expansive) were placed inside the container in layers form, and hummer compaction using a 2.5 kg rammer was conducted by referring to the ASTM D-1557 method to obtain the required density. After the compaction, the GPA was installed in the soil after making a hole using a PVC pipe. The top footing plate was levelled by using a bubble level.

The load was applied using a compression machine at a 0.001 mm/min loading rate. The given speed was considered in order to avoid any potential strain rate effect. At slow loading rate, the equilibrium state can be reached at each loading stage. Also, for such soil which shows time-dependent behaviour, slow loading is essential to minimise the generation of excess pore water pressure to ensure accurate results that present the resistance of the soil solely. Similar studies conducted experiments based on similar strain rate (Huat *et al*, 2006; Mohamed & Vanapalli, 2007). The soil compression was recorded using an accurate dial gauge for measuring displacement. The dial gauge indicator records the force readings throughout the compression phase.

Figure 4. Set-up of the physical model with the loading machine.

Water was continuously pumped from the container's base by a water pump that was controlled by a valve, and water was added from the top to gently wet the expansive soil bed. The soil was allowed to be saturated by water pumping through a valve fixed at the base of the container. To achieve saturation conditions, a special device (Watermark Monitor Device 900M) was used to monitor the saturation of clay and record the degree of saturation with the suction. Five calibrated sensors were embedded in the soil bed at different depths (100 mm, 200 mm, 300 mm, 400 mm and 500 mm) and connected to the Watermark Monitor Data Logger, as shown in Figure 5. The saturation process took 21 days until the readings showed fully saturated conditions. The expansive soil was left under saturation, and the amount of heave was measured. The measurement of heave was monitored continuously until no more swelling was observed.

Once the expansive soil was fully saturated, the load was applied on expansive soil, similar to the loading approach followed in the Oedometer test. The load that brings the soil volume to the original volume was taken as the uplift pressure.

Figure 5. Five calibrated sensors are embedded in the soil bed to monitor the soil saturation.

The experimental findings of heave behaviour in relation to uplift force for the expansive soil with GPA foundation are displayed in Figure 6. The outcomes of the experiments demonstrate that the soil has improved in terms of heave reduction and uplift force degradation. Table 3 shows the heave and swelling pressure values with and without GPA. The GPA reduced both heave and swelling pressure, and as the length of the GPA increases, the effect of GPA in reducing the heave and swelling pressure increases.

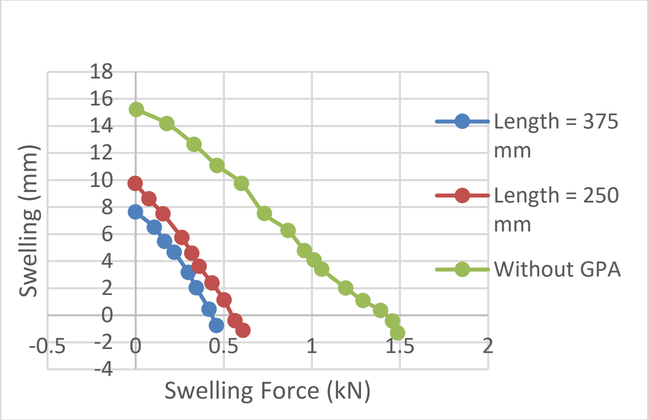

Figure 6. Results of heave with respect to the uplift force of GPA-reinforced soil (with rod lengths of 375 mm and 250 mm).

Table 3. Values of heave and swelling force of expansive soil obtained from the physical model

Test Condition	**Heave (mm)**	**Swelling Force (kN)**
Expansive soil without GPA	15.3	1.47
Expansive soil with GPA L=250 mm	8.9	0.55
Expansive soil with GPA L=375 mm	7.8	0.5

By comparing the results obtained from the experimental (physical) and numerical models, very good agreement was observed, as shown in Figure 7. The trend of results is consistent with those obtained from the experimental results. The consistent results obtained from both models promote the reliability of the simulation results obtained using PLAXIS 3D by following the proposed technique.

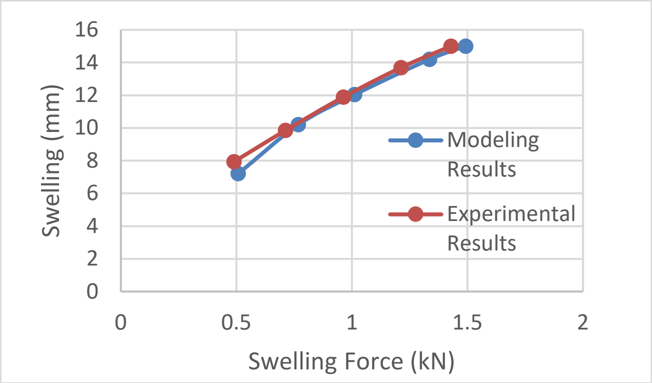

Figure 7. Results of heave from the numerical modelling and the experiments.

The small difference in results between both models might be attributed to the fact that the experimental tests are recognised with less accuracy, as they are subjected to minor errors during the test setting process, compared to the numerical results based on the ideal condition during the numerical analysis.

V. CONCLUSION

The following conclusions can be drawn from the findings of this study

- The heave and uplift pressure of expansive soil was significantly reduced after using the GPA technique.
- The proposed technique proved to be a reliable way to measure expansive soil's heave and uplift pressure since the results obtained from the proposed technique were validated and compared with those obtained from the physical model.
- The performance of GPA in reducing the heave and uplift pressure of expansive soil was affected by the length of the rod of GPA, it increases as the GPA rod increases.
- GPA contributed to an improvement of almost 50% of the expansive soil in reducing the heave and uplift pressure compared to unreinforced soil conditions.

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