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INVESTIGATING THE EFFECT OF COMPACTION DEGREE AND THE PARTICLE SIZE DISTRIBUTION OF THE FILLING MATERIAL ON THE PULL-OUT CAPACITY OF GRANULAR PILE ANCHOR FOUNDATION

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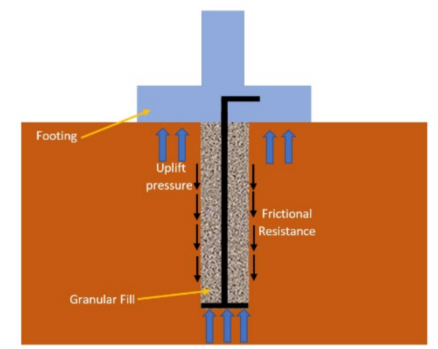
Graphical abstract



Abstract

A Granular Pile Anchored Foundation (GPAF) is a technique that was used as a ground improvement technique for the soils that experience significant volumetric strain. The efficiency of GPAF is affected by the type of filling material that is responsible to develop the frictional resistance along the surrounding soil interface. Two types of filling materials were employed in this study; sand and crushed stone. GPAF was investigated by using sand material at different compaction degrees, and by using crushed stone at different particle size distributions. The results showed the variations in pull-out capacity which increased as the compaction degree increase. Similarly, the GPAF with filling material of coarse particles of crushed stone showed higher pull-out capacity compared to that for filling material with fine particles of crushed stone. This behaviour was attributed to the frictional resistance that was increased due to the increase of friction degree caused by high compaction degree for sand, and coarse materials for crushed stone samples. Therefore, this study is emphasizing the importance of selecting appropriate filling material used in GPAF in increasing the pull-out capacity of GPAF.
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Keywords: expansive soil, ground improvement, granular pile anchor foundation, heave, pull-out capacity

1.0 INTRODUCTION

Expansive soil experiences volume change (swell and shrinkage) upon changing the water content. Lightweight structures are prone to failure due to uplift movement when they are built on shallow foundations [1]. Among the proposed solutions to mitigate the effect of expansive soil's heave and uplift pressure is the Granular Pile Anchored Foundation (GPAF) developed by Phanikumar et al. (2004) [2].

GPAF is considered a soil improvement technique that delivers cost-effective solutions to improve the shearing capacity and overcome the uplift force of the expansive soil. A typical GPAF can be constructed after making a borehole in a previously specified point under the building foundation. A steel rod attached to a steel plate at the bottom end shall be inserted inside the borehole and filled with filling materials such as sand, crushed stone or boulders. The top end of the steel rod is connected to the main foundation. This system is expected to withstand the uplift pressure developed under the main foundation through the GPAF self-weight, the frictional resistance between the filling material and the surrounding soil, and the lateral soil pressure of the expansive soil that increases the frictional resistance along the GPAF-soil interface [3].

Several studies [4-8] were presented to investigate the effectiveness and the factors affecting the performance of GPAF. Most of these studies agreed that increasing the efficiency of GPAF depends on increasing the frictional resistance area delivered in the contact surface between the granular fill of GPAF and the surrounding expansive soil.

The frictional resistance area can be increased by enlarging the diameter and length of GPAF. Also, considering filling material with a higher friction angle would increase the frictional resistance of GPAF. Notably, the lateral pressure of expansive soil of the GPAF would be advantageous to increase the frictional resistance of GPAF as it imposes pressure on GPAF laterally.

This paper aims to investigate the role of the filling material in GPAF and its effect on the pull-out capacity through performing Finite Element Modelling of GPAF at different lengths and different filling materials.

1.1 Concept of GPAF

The GPAF is a foundation system invented to resist any uplift force and consequently support the stability of structures. The key feature of the GPAF is the anchorage that links the base plate with the anchor attached to the top footing. The granular material, that fills the hole of a GPAF, develops frictional resistance with the surrounding soil that prevents the top footing from any potential upward movement, as shown in Figure 1. In other words, the difference between the conventional stone columns and GPAF is the anchorage system (base plate, steel rod, and the top anchor), since the latter delivers tensile strength against uplift force. A proper design process usually takes place for the proposed GPAF after conducting a site investigation to determine the engineering properties of the soil and to specify the thickness of the expansive soil. During the design phase, GPAF length, diameter and the type of filling material are specified. After installing the GPAF in the designated locations, testing of pull-out capacity and monitoring for the performance of GPAF are usually conducted before constructing the superstructure.

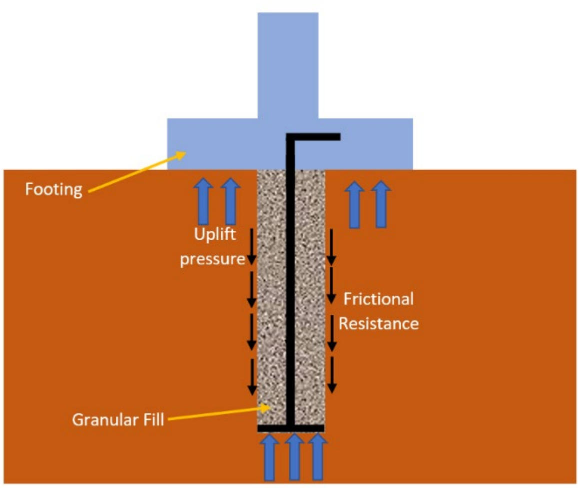

Figure 1 Schematic diagram of a granular pile anchored foundation in an expansive soil

2.0 RESEARCH METHODOLOGY

The main results of this study were obtained after performing numerical modelling which considered the core of this study. However, there was an essential need to conduct preliminary tests to measure necessary parameters that shall be used as inputs for the modelling process.

2.1 Preliminary Tests

In this study, sand and crushed stones were considered as filling materials in GPAF. However, the crushed stone material was prepared in four samples that differ in their gradations. Limestone material was collected from a quarry in the south west part of Iraq. Later, samples were crushed to produce crushed stone material with different gradations. The sand was easily collected as construction sand from the market.

The gradation parameters of sand and crushed stone samples are shown in Table 1. The gradation indexes were used as input parameters in the modelling process. On the other hand, preliminary tests were performed on the test materials to determine the physical properties which are essential for modelling. Maximum dry density (MDD) is one of the physical properties that was determined through the experimental work since the MDD of the sand is considered for modelling the GPAF with sand filling at different compaction degrees. The compaction degree was found by referring to the MDD which was found through conducting the standard proctor test. The MDD of sand was determined as of 1.89 t/m^3 and the compaction degree values of 70%, 80% and 90% were derived from the given MDD value. The preliminary tests are very important to ensure a modelling process is based on real sample data.

Table 1 Gradation parameters of the test materials

Gradation parameter	Sample A	Sample B	Sample C	Sample D	Sand
C_u	1.95	1.99	10.25	13.05	2.41
C_c	0.96	0.97	3.97	2.98	0.82
D_{60} (mm)	8.04	6.84	5.63	5.56	0.68
D_{30} (mm)	5.65	4.82	3.43	2.48	0.41
D_{10} (mm)	4.16	3.54	0.57	0.35	0.28

2.2 Numerical Modelling

PLAXIS 3D was utilized to simulate the behavior of the GPAF under pull-out loading conditions, aiming to assess its pull-out capacity when filled with sand and various gradations of crushed stone.

The GPAF typically comprises four main elements: an anchor attached to the top foundation resting on expansive soil, a steel rod at the core of the stone column, a base plate at the bottom end of the rod, and the filling material (comprising sand and crushed stone), which offers frictional resistance along the GPAF-soil interface to resist the uplift pressure. A modelled GPAF is shown in Figure 2.

The Hardening Soil (HS) model was considered for modelling the soil around the GPAF at undrained conditions. However, steel elements of GPAF such as the rod, anchor and base plate were modelled by using the Linear Elastic (LE) model. This model was considered for steel items to avoid any unnecessary deformation upon applying the pull-out loads. On the other hand, Mohr-Coulomb (MC) model was utilized for modelling the filling materials used in this study (sand and crushed stone). All selected models were considered after many trials and error attempts and several analysis processes conducted on the model. the modelling process is consistent with the numerical study by Ismail & Shahin (2011) [9].

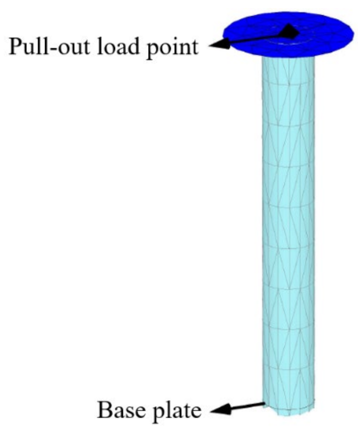

Figure 2 Modelling of GPAF by using Plaxis 3D

3.0 RESULTS AND DISCUSSION

Understanding the resistance of GPAF toward the uplift force caused by the expansive soil is very essential for designing the GPAF for field applications. The pull-out capacity of GPAF given as a pullout-displacement curve indicates the GPAF resistance to the upward force of expansive soil. Such results indicate the foundation settlement anchored to the GPAF subjected to expansive soil's uplift force. There are several factors affect the performance of GPAF in resisting the uplift pressure developed by the heave of expansive soil. An experimental evaluation for some of those factors is given in the following sections.

3.1 Effect of Compaction Degree

GPAF was modelled at a pile diameter of 0.8 m and lengths of 3 m, 5 m, and 7 m. At a given pile length, the filling material was modelled at a compaction degree of 70%, 80% and 90%, then the pull-out load was applied at each GPAF model. The pull-out capacity can be evaluated by referring to the upward displacement corresponding to the applied pull-out load on the GPAF. Figures 3, 4, and 5 show the pull-out load versus displacement curves of GPAF lengths of 3 m, 5 m, and 7 m, respectively. The results showed that the maximum pull-out capacity was reported from the GPAF length of 7 m that has sand filling a compaction degree of 90%.

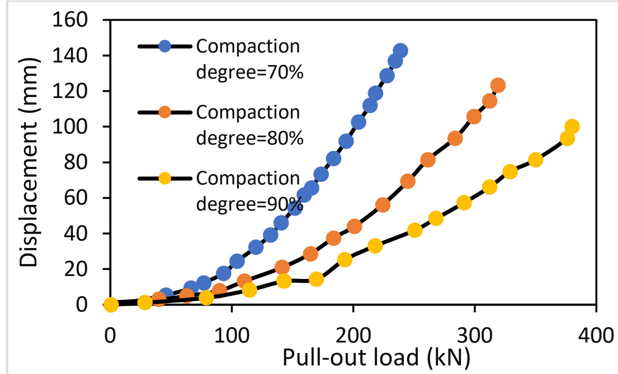

Figure 3 Pullout-displacement curves of GPAF lengths of 3 m with filling material at different compaction degrees

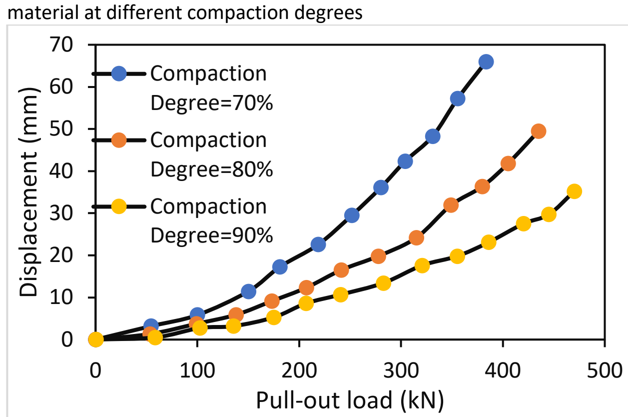

Figure 4 Pullout-displacement curves of GPAF lengths of 5 m with filling material at different compaction degrees

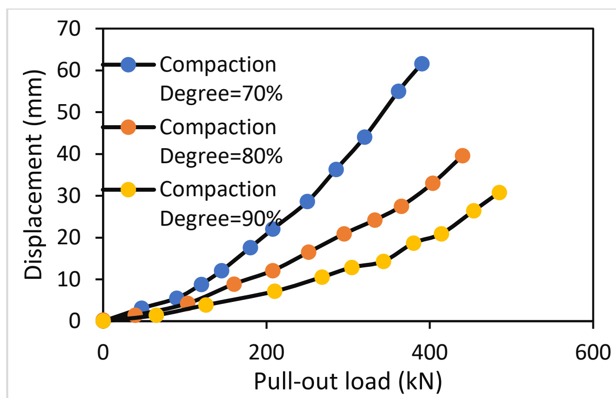

Figure 5 Pullout-displacement curves of GPAF lengths of 7 m with filling material at different compaction degrees

It can be observed from all test results that at the initial stage of the pull-out loading, there is no significant increase in the upward displacement. This behaviour can be attributed to the weight of GPAF that far greater than the pull-out load imposed on the GPAF at the early stages of loading. Also, increasing the GPAF length would lead to friction surface area increase and GPAF overall weight, and that would consequently lead to increasing the pull-out capacity.

Additionally, the results highlight that, at each loading stage, the pull-out load needed to induce a specific upward displacement increases with the increasing length of the GPAF.

3.2 Effect Of Particle Size Distribution

Sample A, sample B, sample C, and sample D, are crushed stone materials that have different particle size distribution curves. They are named by order from low fine content to high fine content (sample D has the highest fine content among the four samples). Crushed stone samples were used as a filling material for modelling the GPAF at lengths of 3 m, 5 m and 7 m. Figures 6, 7, and 8 are illustrating the pull-out capacity of crushed stone-filled GPAF at lengths of 3m, 5m, and 7m. The results indicated that the 7 m-length GPAF that was filled with crushed stone from (Sample A) achieved the highest pull-out capacity compared to the rest samples. This behaviour is attributed to the high frictional resistance developed by the filling material from sample A, which has a high friction angle compared to other samples, and the surrounding soil However, at a given GPAF length, the results confirmed that the higher the fine content the greater the displacement under a given pull-out load.

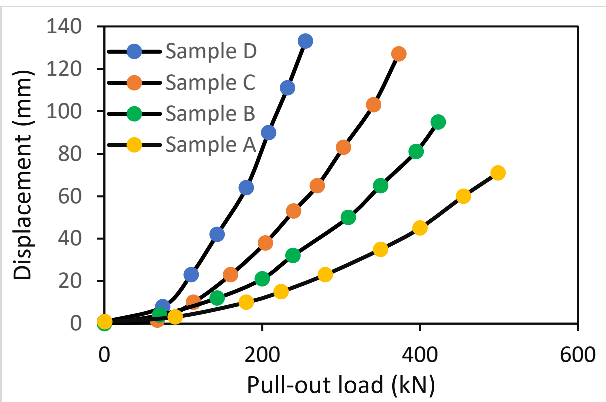

Figure 6 Pullout-displacement curves of GPAF lengths of 3 m with filling material at different gradations

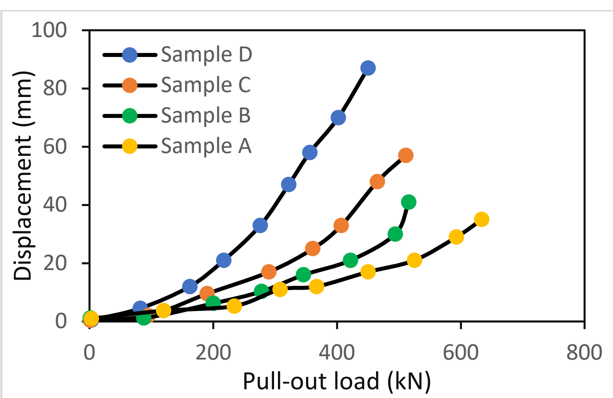

Figure 7 Pullout-displacement curves of GPAF lengths of 5 m with filling material at different gradations

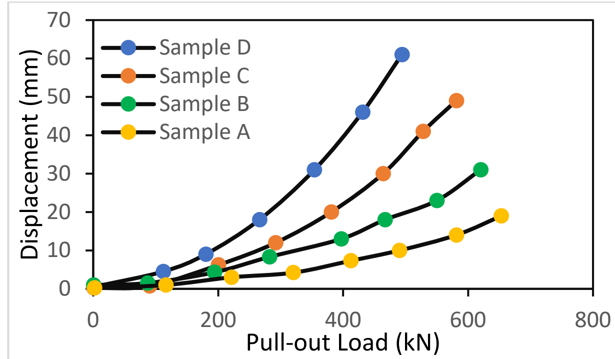

Figure 8 Pullout-displacement curves of GPAF lengths of 7 m with filling material at different gradations

The GPAF gains pull-out resistance against the uplift force from the self-weight of GPA, as well as the friction between the soil and the granular interface [10]. The larger the frictional resistance area, the higher the GPAF pull-out capacity. On the other hand, the expansive soil is typically expanding in vertical and horizontal dimensions. The lateral expansion of expansive soil on the GPA contributed to the pull-out resistance since the lateral expansion imposed lateral forces on the GPAF that increased the frictional resistance of the GPAF.

Previous studies on GPAF, such as Kumar and Rao (2000), Bagheri et al. (2024), Nusier et al. (2023) and Khan et al. (2024) [3,10,5,11], have used the concept of the pull-out capacity to examine the potential of the GPA to withstand external forces applied to pull the GPA out of the soil. Their results are consistent with the results obtained from this study.

3.3 Effect of Relative Density

The effect of the relative density of the granular material in FPAF on the pull-out capacity of GPAF was evaluated by considering three different relative density values at different GPAF lengths. Relative density values of 50%, 70% and 90% were used during the modelling process by using Plaxis 3D, however, the other essential engineering properties of the granular material were taken similar to those considered for Sample A. Figures 9, 10 and 11 show the effect of changing the relative density at GPAF lengths of 3 m, 5 m, and 7 m, respectively. The results are clearly indicating that as the relative density increases, the pull-out capacity increases. This behaviour was reported because of the increase in the relative density increase that was attributed to increasing the frictional resistance between the granular material and the surrounding soil which helped to resist the pull-out loads applied on the GPAF. Also, with a higher relative density of granular material of GPAF, the risk of pull-out failure is less because the applied pull-out load is transferred within the GPAF more effectively as there is no potential of particles rearrangement upon loading. Several studies [12,13,14] agree with the trend of results obtained from this study.

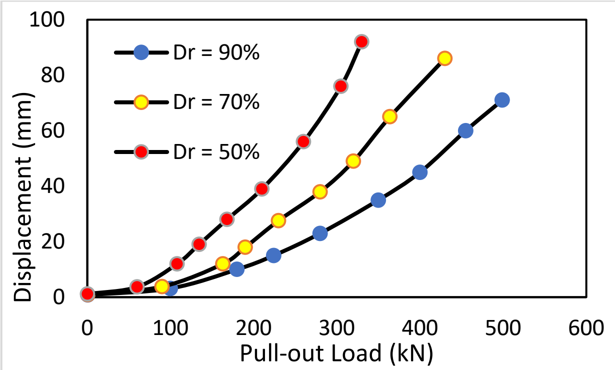

Figure 9 Pullout-displacement curves of GPAF lengths of 3 m with filling material at different values of relative density

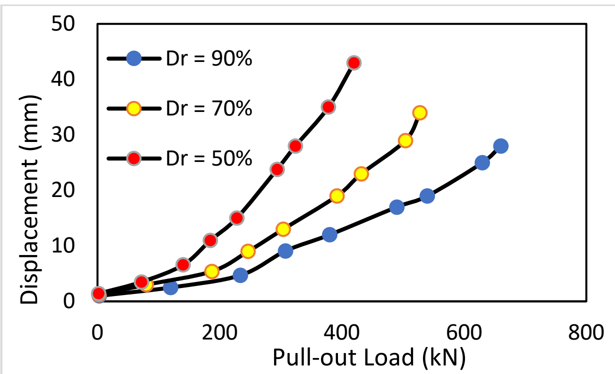

Figure 10 Pullout-displacement curves of GPAF lengths of 5 m with filling material at different values of relative density

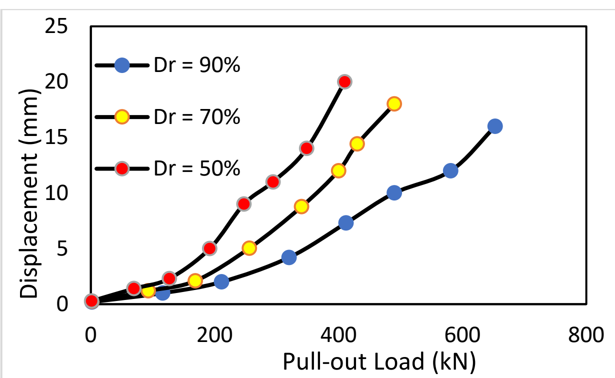

Figure 11 Pullout-displacement curves of GPAF lengths of 7 m with filling material at different values of relative density

4.0 CONCLUSION

The following conclusions were drawn from the findings of the results

- GPAF is an innovative technique to overcome the uplift pressure of the expansive soil and consequently ensure the settlement of the foundation attached to the GPAF.
- The pull-out capacity of GPAF is significantly affected by the length of the pile. The longer the pile the higher pull-out capacity.
- The frictional resistance that contributes to the pull-out capacity is dependant on the frictional surface area between the filling material and the surrounding soil.
- The compaction degree of the sand with the GPAF plays vital role in increasing the pull-out capacity of GPAF. Higher pull-out capacity was reported from GPAF with higher compaction degree.
- The crushed stone filling material that contains low fine content contributed to higher pull-out capacity of GPAF. The reason behind this behaviour is the friction degree that reported higher value compared to those with high fine content.
- The increase of relative density of the filling material contributed to increasing the pull-out capacity of GPAF. Less relative density was the reason for pull-out failure at relatively low pull-out loads

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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