Finite Element Modeling of Innovative Shallow Raft Foundation with Granular Pile Anchor System for Expansive Clays

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Abstract. Granular pile anchor foundations (GPAF) are considered a significant promising foundation system to alleviate the serious effects of changes in the volume of expansive soils that occur throughout shrinkage and expansion. In this paper, 3D finite element analyses are presented by applying PLAXIS software, which is carried out on a typical double-story building built over a GPAF system in expansive soil. An investigation on GPAF system is presented in terms of its resistance ability to the forces caused by the soil movement as a result of variant moisture and the effect of the resistance on the superstructure induced by the straining actions. The results indicate the significance of the GPAF system in restricting the soil movement with high efficiency, which results in a noticeable improvement in the building structural responses in terms of uplift forces, heave and induced deformations.

1. Introduction
Expansive soils are considered as clays that could shrink and expand with variation in the moisture content, and it can be found in many dry and semi dry regions around the globe. For instance, 20% of the surface soil in Australia can be considered as reactive [1]. There are some elements that affect the shrinking and expansion of clay soils, which include cation, exchange capacities, the type and volume of clay soil minerals and the existence of initial water content and moisture. The challenges associated with reactive soils in terms of shrinking/swelling ground movements are uprising to the geotechnical community due to the resultant effects of such soils in terms of the distress caused to the structures of the lightweight foundations, the cracking in retaining walls, linings, canal beds, and pavements [2-3].

There are still huge financial losses in many regions of the world, in spite of having various foundations systems for controlling the movements associated with reactive soils. Statistics indicated by the American Society of Civil Engineers show that approximately one quarter of all US houses have suffered some damage cause by reactive soils, besides, the financial losses of the property owners are more than caused by a combined natural disasters such as hurricanes, floods, tornados, and earthquakes [4]. In Australia, lightweight buildings experience an early damage caused by the reactive soils in spite
of the strict Australian regulatory requirements [5]. There are several solutions in the literature implemented by researchers on reactive soils, such as pile foundations, replacing the whole layer of reactive soil [6], stabilizing the soil by using additives [7-8] or by implementing special foundations such as friction piers and drilled [3]. The granular pile anchor foundation (GPAF) is a recent proposed promising foundation solution and it is has shown noticeably a great potential in reactive soils with high efficiency in reducing the damages caused by such clays, hence it is an innovative solution. Phanikumar and Ramachandra Rao [9] firstly proposed the GPAF system under heave conditions for reactive soils then was followed later by other researchers through filed trials and laboratory work [10-11].

In order to determine the controlling parameters of the GPAF system, further investigation on the efficiency of such technique was needed using the finite element method (FEM) as it was firstly examined by Shahin and Ismail [12]. In spite of the significance of the GPAF technic in restricting the movement of the soil as mentioned in the literature, however, it is not applied in practice yet mainly due to the limited field trials. In this paper, a numerical 3 dimensional (3D) analysis for a foundation structure of a typical double-storey, four-bay structure in reactive soil to examine the performance of the GPAF during shrinkage and expansion. The efficiency of the GPAF technique in controlling the ground movements associated by soil shrinkage/heave is examined and also the association of this on the superstructure internal forces is further investigated.

2. Concept of GPAF system
The concept of GPAF system is illustrated in Figure 1 which is considered as a hybrid solution that indicates the support of a shallow foundation on a granular pile in which derives its resistance from the interface between the nearby reactive soil and the granular pile. Figure 1 shows the GPAF system which contains of the pile of granular material set up into the reactive zone and continues to the saturated layer to increase the uplifting and heave resistance ability of GPAS. A steel anchor is built above the granular pile and it is connected to the pile through a concrete footing that is casted rigidly to be able to transfer the load between the pile and the footing. In this system, along the boundary of granular pile, the uplift resistance is deployed as skin friction at the interface region with the surrounding soil.

Furthermore, a rigid base plate that is connected to the pile anchor is considered as a medium for interface where the pile anchor force is transmitted to. Based on this system design arrangement, the granular pile can efficiently reinforce the ground (for example the loose sand soft clay) and resist the expansive soil induced uplift forces effectively. The GPAF system uplift resistance is a function of various factors such as the self-weight of the pile footing, the granular pile surface area, normal stress caused during the soil expansion and the interface shear strength. As can be seen in [13], there is an increase about 6.6 % in the shallow shear strength of the expansive soil around the pile compared to the free field zone clay as a result of the normal stress induced from the expansion.
Figure 1. Typical GPAF system

3. Double-storey building numerical analysis based on GPAF system.

In order to examine the performance efficiency of the GPAF system in real practice, three models were developed; one is for free swelling of the expansive clay, second model was for building rest on raft foundation with load 30kN/m$^2$ and third model is for building resting on raft foundation which rest on group granular pile anchor. Models were analysed numerically by using PLAXIS 3D foundation software for finite element [14-16].

3.1. Problem identification

The dimensions of the proposed double-storey building is 3 m height for each storey which accumulates 6 m height for the double-storey and it is $11.20m \times 11.20 m (W \times L)$ and 2.4 m $\times$ 2.4 m dimensions of each bay. In each storey, an assumed thickness of 160 m for the ceiling slab. The dimensions of the beams supporting the slabs are 300 mm deep and 300 mm wide. These slabs rest on square columns with dimensions of 300 mm $\times$ 300 mm. One main factor is considered for calculating the structural component dead load of the frame building which is the weight of the material unit in that component, besides assuming a distributed live load of 9 kPa applied on the top of the slabs. The specifications of the concrete materials were considered as a concrete with unit weight of 24 kN/ m$^3$, Poisson’s ratio of 0.2 and an elastic modulus of 37 GPa. The raft foundation distribution load was 30kN/m$^2$.

The GPAF system consists of raft foundation with dimensions $11.20m \times 11.20 m \times 0.25m$, is supported by 25 angular piles with 8 m length and a diameter of 0.8 m with a measured distance of 2.4 m between pile and other. Figure 2 displays the organization of the group granular piles within the pad footing. The enhancement of the stability of the system and the rotational stiffness is implemented by using a group of piles instead of using a single pile. Figure 3 shows 3D raft footing with distribution GPAF.
The ideal ground profile has an expansive clay layer of 4 m and an average thickness covering the non-expansive clay (saturated clay) with 16 m. It is worth mentioning that the 4 m layer is the responsible for causing the heave and shrinkage event while the stable zone (saturated clay) is considered stable because there is no moisture variation over time. In order to enhance the analysis accuracy, the model was refined around the granular piles and the footing and in order to reduce the effect of the boundary, these boundaries are placed far from the area of interest. The footings of the concrete were placed about 0.0 m on the surface of the ground and a place element of Mindlin’s with 0.25 m thickness were used to model the concrete footings.

**Figure 2.** Arrangement of the group granular piles dimensions

**Figure 3.** FEM 3D model of Raft and GPAF
3.2 The models and the parameters of the Soil

The model used for reactive clay was the hardening soil constitutive model (HS) with an assumed undrained manner behavior during expansion. Mohr-Coulomb (MC) model was used to model the granular pile. The HS model is considered as a non-linear plastic elastic formulation that embraces multiple loci as plastic shear strain function and as a cap to permit volumetric hardening [14]. The hyperbolic formula represents the relationship of the non-linear stress strain, with an initial loading that is governed by a secant deformation modulus ($E_{50}$) at a material strength of 50 %. An elastic unloading and loading were assumed within the current yield surface and the Mohr-Coulomb failure criterion governs its failure. According to the following formula, the evolvement of $E_{50}$ and $E_{oed}$ occurs with the minor effective stress, $\sigma_3$ as shown below:

$$E_{50} = E_{50}^{ref} \left( \frac{c \cos \varnothing - \sigma_3 \sin \varnothing}{c \cos \varnothing + p_{ref} \sin \varnothing} \right)^m$$

(1)

Where: $c$ is the soil effective cohesion, $\varnothing$ represents the friction angle, $m$ represents the exponential factor that controls the dependency of the stiffness on stress and $p_{ref}$ is the reference stress corresponding to $E_{50}^{ref}$. Table 1 summarizes the parameters of the expansive clay evolving after the wetting/drying and during expansion/shrinking event. It is worth mentioning that, in reality, the strength of expansive soils decreases during expansion and increases during shrinking (due to suction) which was not modeled in this study.

However, the rate of volume change of the expansive clays depends on the magnitude of overburden pressure and location from the source of moisture. In the current study, a leaking occasion of an underground water capability existed underneath the column center was assumed to heave of 6.6% over the thickness of the affected area underneath the central footing, as shown in Figure 3b. Both heave and shrinkage were modeled by applying equal volumetric strains over the layer thickness of modeled soil. The heave was applied independently starting from the stage after application of the dead and live loads.

Table 1. The properties of the soil for analyzing the finite element.

| Parameter                        | Expansive Clay | Stable Clay | Granular Pile |
|----------------------------------|----------------|-------------|---------------|
| $\gamma_{sat}$ ( KN/ m$^3$)      | 16.33          | 16.33       | 17            |
| $\gamma_{sat}$ ( KN/ m$^3$)      | 19             | 19          | 20            |
| $C'$ ( KN/ m$^2$)                | 30             | 30          | 3             |
| $\phi'$                          | 22             | 22          | 42            |
| Volumetric strain%(swelling)     | 6.6            | -           | -             |
| Volumetric shrinkage%            | 1.7            | -           | -             |
| $E_{50}^{ref}$                   | 3500           | 3500        | 28x10$^3$     |
| $E_{oed}^{ref}$                  | 3000           | 3000        | 84x10$^3$     |
| Vur                              | 0.2            | 0.2         | 0.25          |

4. Results and discussion

The performance efficiency of the GPAF system over a reactive soil to enhance a double-storey building was investigated based on three models namely; soil without loading, soil without GPAS (building self-weight ) and building with GPAS. The comparison among the three models in terms of heave and uplift force is shown in Figure 4. The comparison was made for the top raft at central plan and at edge. It is obvious that the constructed building with GPAS foundation system enhances substantially the expansive soil in terms of heave and uplift force.
Table 2 presents the average heave with three case model to compare the results of the induced deformations. The heave was 0.26 m in plain soil without constructed house and GPAS foundation. The heave was reduced by 8 % (0.24 m) and further reduced by 98.6 % (0.004 m) when the GPAS was introduced. Furthermore, the uplift force improvement is summarised in Table 3. The uplift force for plain soil was found to be 715 kN. On the other hand, significant improvement was found in building without GPAS and building with GPAS 4 % (685 kN) and 96 % (47) respectively. Hence, it is obvious the applicability of the GPAS system to arrest the heave and uplift force resulted in expansive soil. This improvement is induced by the frictional forces alongside the GPA and soil interface.

Table 2. Average heave three case of models

| Type of building          | Soil without loading (free heave) | Building without GPAS | Building with GPAS |
|---------------------------|-----------------------------------|-----------------------|--------------------|
| Heave(m)                  | 0.26                              | 0.24                  | 0.004              |
| Degree of improvement     | 0%                                | 8%                    | 98.6%              |

Table 3. Average Uplift forces three case of models

| Type of building          | Soil without loading (free heave) | Building without GPAS | Building with GPAS |
|---------------------------|-----------------------------------|-----------------------|--------------------|
| uplift force kN            | 715                                | 685                   | 47                 |
| Degree of improvement     | 0%                                 | 4%                    | 96%                |
5. Conclusion
The results analysis of the 3D FEM of the GPAF system were presented as a viable solution for lightweight structures over expensive soils. Besides, the response of the superstructure double-storey building with four-bay frame to the ground have/uplift pressure caused by reactive soils was investigated. The presented results show the significance of the GPAF system in reducing the heave and uplift forces caused by expensive soil, hence it is considered an efficient system. The degree of improvement for the heave when applying GPAS was 98.6% while the degree of improvement for uplift force was found to be 96 %. This shows the potential for the GPAS system as a simple and effective foundation system to mitigate the expansive soil problems in terms of heave and uplift forces due the frictional properties alongside the interface between the GPA and the expansive soil.

6. References

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