

Finite Element Analyses of Granular Pile Anchors as a Foundation Option for Reactive Soils

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Synopsis: Laboratory and field studies have shown that granular pile-anchor foundations (GPAF) are a promising foundation system that can be used to reduce the detrimental effects of reactive soils. This paper presents results from finite element analyses undertaken on granular pile-anchor foundations in a reactive soil using PLAXIS software. The study investigated the ability of a single pile to resist forces induced by both heave and shrinkage. The results confirmed the efficiency of the granular pile-anchor foundations in resisting heave induced by moisture gain. However, in order to resist shrinkage, the GPAF system has to be reinforced with geofabric to assist resisting bulging of the granular pile into the surrounding soil. The analyses showed that success of the GPAF in heave resistance may be adversely influenced by the high stiffness of the interface, which requires only small relative movement to mobilize full resistance. Using a group of piles instead of a single pile under a footing can reduce the efficiency of the GPAF system.

Keywords: reactive soil, foundation, granular pile, PLAXIS, swelling, shrinkage, geofabric.

1. Introduction

Reactive soils pose significant challenges to the geotechnical communities due to their potential to cause ground movement with changing moisture content, thereby causing distress to foundations of low-storey buildings and cracking in retaining walls, pavements, canal beds and linings [e.g., 1, 2]. Although the risk associated with foundations on reactive soils have been long recognized, especially in developed countries, problems associated with these soils are ever increasing. For example, the American Society of Civil Engineers estimated that about one quarter of all homes in the US have experienced some damage from reactive soils; the financial losses incurred by property owners exceed those caused by natural disasters such as earthquakes, floods, hurricanes and tornadoes combined [3]. In Australia, and despite the stringent regulatory requirements, most of the lightweight buildings constructed on reactive soils experience some distortional damage during their early lives [4].

Since recognition of the problematic nature of reactive soils, numerous solutions have been proposed, including replacement of the entire reactive material, soil stabilisation using a variety of additives [e.g., 5, 6], pile foundations [e.g., 7] and implementation of special types of foundations such as drilled and friction piers [1]. One promising, special foundation solution that was first proposed for reactive soils (under heave conditions) is the granular pile-anchor foundation system (GPAF) [8]. Investigation into this foundation technique was further pursued by other investigators during the last decade [e.g., 9, 10]. As detailed in the next section, the GPFA is a hybrid solution in which shallow foundations are supported on granular piles that derive their resistance from the interface between the granular piles and surrounding reactive soil. Despite the success of the GPFA reported by the above investigators, the technique is yet to be applied in practice, primarily due to the limited field trials with the technique. One other serious limitation of the GPFA, as presented so far in the literature, is the ambiguity related to its performance when the reactive soils lose moisture and experience shrinkage rather than heave.

This paper investigates the performance of the GPFA system under heave, using the finite elements method (FEM), in an attempt to understand the behaviour of this promising technique and to determine its controlling parameters. Moreover, the paper presents a modification to the technique that ensures its capability to resist forces resulting from shrinkage by enclosing the granular pile into a geofabric casing.

2. Concept of Granular Pile-Anchor Foundation System

Figure 1 shows the concept of GPAF system, which consists of a pile of granular material compacted into a borehole that is made into the reactive soil. A concrete footing is then constructed above the granular pile. In order for the pile to prevent upward movement of the footing during heave of the reactive soil, the footing has to transfer the uplift pressure down the granular pile via a steel anchor that is monolithically

casted with the concrete footing. According to this concept, the uplift resistance is ultimately mobilized as shearing stress along the interface of the granular pile. The force in the pile anchor is transmitted to this interface by virtue of a base plate that is rigidly connected to the anchor (Figure 1). According to this arrangement of the anchorage system between the footing and granular pile, the latter cannot only reinforce the ground (as in the case of soft clay and loose sand) but can also effectively resist the uplift forces from reactive soils. According to Figure 1, the uplift resistance of the GPAF system is a function of the self weight of the pile-footing assembly, interface shear strength, surface area of the granular pile and normal stress developed during expansion of the soil surrounding the pile.

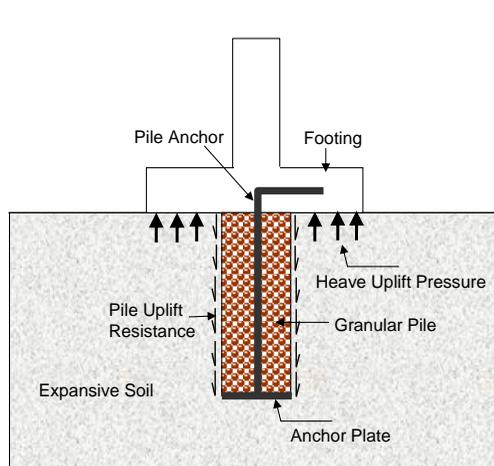


Figure 1. Concept of the GPAF system

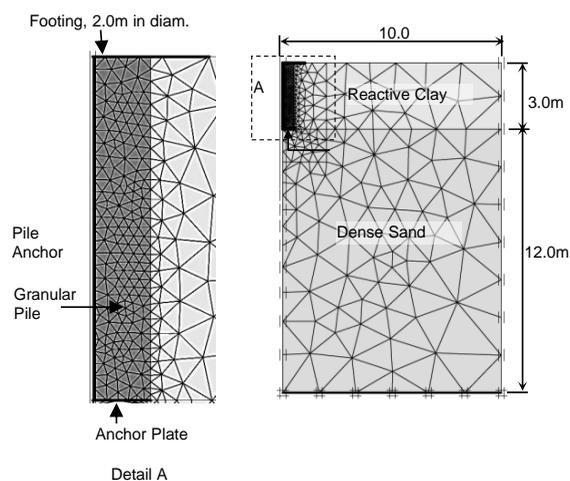


Figure 2. 2D model for a single pile

3. Numerical Analysis of the GPAF System

The behaviour of a footing reinforced with either a single pile or a group of piles was investigated in this paper using numerical analyses. The case of a single pile was analysed as an axi-symmetric problem using PLAXIS 2D software [11], whilst the pile group was analysed as a 3D problem using PLAXIS 3D [12].

3.1 Analysis of a Single Pile

The 2D axi-symmetric model used in the analyses is presented in Figure 2, which consists of about 1000, 15 node triangular elements. The footing diameter was fixed at 2.0 m, and the granular pile length was fixed at 3.0 m. The diameter of the granular pile was varied at 0.25, 0.5, 0.75 and 1.0 m. The objectives of the 2D analyses were: (1) understanding the behaviour of the GPAF system; and (2) determining the influence of the pile geometry.

3.2 Analysis of a Pile Group

The behaviour of a single footing supported on four piles was analysed using the 3D model presented in Figure 3. The model consisted of 7000, 15 node wedge elements of 6 Gaussian point each. The objective of the 3D analyses was to determine the influence of using a pile group of different spacing instead of a single pile. To this end, the analyses covered a pile spacing of $2d$, $3d$ and $4d$ between the piles, where d is the pile diameter. The diameter of each pile in the group was selected such that the combined surface areas of the group are equivalent to that of the single pile case. Accordingly, the diameter of the single pile was 1.6 m, whilst the diameter of each pile in the 4-pile group was 0.4 m. The footing dimensions used in the 3D analyses were equal to 2.5 m x 2.5 m.

For both the 2D and 3D analyses, the idealized ground profile consisted of 3.0 m of reactive clay overlying dense sand. The model was strategically refined around the footing and the granular pile to improve the accuracy of the analysis and the boundaries were located farther from the area of interest to minimize the boundary effect. The concrete footing was modelled using a Mindlin's plate element of an elastic modulus of 35 GPa, a thickness of 0.6 m and Poisson's ratio of 0.15. The pile anchor was modelled as an elastic embedded pile of 30 mm diameter and Young's modulus of 200 GPa.

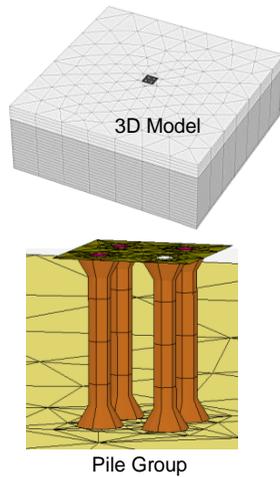


Figure 3. 3D Model for a pile group

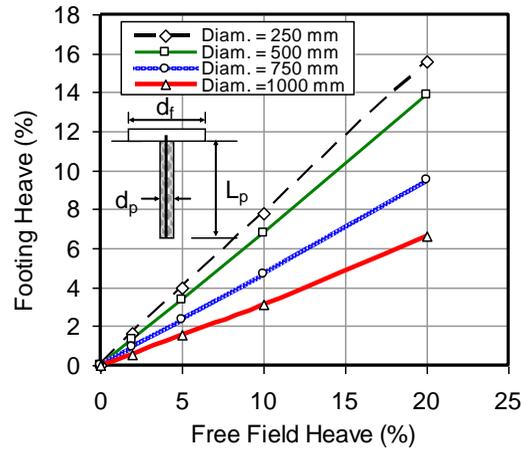


Figure 4. Heave response of a single pile

3.3 Soil Models and Parameters

The reactive clay, the underlying dense sand and granular pile material were modelled using the hardening soil model (HS) in PLAXIS. The HS model [13] is a non-linear elastic plastic formulation which adopts multiple yield loci as a function of plastic shear strain and a cap to allow volumetric hardening. The non-linear stress strain relationship is represented by a hyperbolic formula, with primary loading governed by a secant deformation modulus [E_{50}] at 50% of the material strength. Loading and unloading within the current yield surface are assumed elastic (defined by a separate modulus, E_{ur}) with failure governed by the Mohr-Coulomb failure criterion. Both E_{50} and E_{ur} evolve with the minor effective stress according to the following formula:

$$E_{50} = E_{50}^{ref} \left(\frac{c \cos \phi - \sigma'_3 \sin \phi}{c \cos \phi + p_{ref} \sin \phi} \right)^m \quad (1)$$

where: ϕ is the peak friction angle, m is the exponent that controls dependency of the stiffness on stress and p_{ref} is the reference stress corresponding to E_{50}^{ref} . A summary of the parameters used for all soils are presented in Table 1. The properties of clay were those evolving after the wetting event and during expansion (strictly speaking, the strength of a reactive soil degrades during expansion, but this was not modelled in this study). The clay layer was assumed to behave in an undrained manner during expansion.

Table 1. Material properties used in the finite element analyses

Soil Layer	γ_d	$E_{50} (ref)$	$E_{oed} (ref)$	$E_{ur} (ref)$	$c' (ref)$	ϕ'	ν_{ur}	$p' (ref)$	m	K_0
	(kN/m ³)	(MPa)	(MPa)	(MPa)	(kPa)	(°)		(kPa)		
Reactive Clay	18	2	2	6	2	24	0.2	50	0.5	0.5
Dense Sand (drained)	20	75	75	200	0.1	36	0.2	100	0.5	0.4
Granular Pile (drained)	22	200	200	600	0.1	40	0.2	100	0.5	0.4

Note: $E_{50(ref)}$ is the deformation modulus at 50% of strength at reference pressure $p_{(ref)}$; $E_{ur(ref)}$ is the unload-reload deformation modulus at reference pressure; $E_{oed(ref)}$ is the incremental constrained modulus at reference pressure; ν_{ur} is the unload-reload Poisson's ratio; m defines dependency of stiffness on lateral effective stress.

3.4 Modelling Soil Heave and Shrinkage

Heave and shrinkage of the reactive clay were modelled by applying a volumetric strain to the reactive clay layer. In reality, the rate at which a reactive clay would normally expand depends on the location from the source of moisture and magnitude of overburden pressure. However, for simplicity, in the analyses presented herein, the volumetric strain was applied uniformly across the full thickness of the clay layer.

4. Results and Analyses

4.1 Behaviour of a Single Pile under Heave

Efficiency of the GPAF system in arresting the deformation of a foundation is clearly illustrated in Figure 4 above, which shows the heave response of the single footing modelled in the 2D analysis versus the free field heave. As expected, the figure shows that the footing movement is strongly dependent on the pile diameter; the ability of the system to resist various rates of heave seems to improve with increasing the pile diameter. The shear mechanism mobilized around the granular pile during the modelled heave event is manifested as rotation of the principal stresses, as depicted in Figure 5. This figure shows clearly that the plane of maximum shear stresses rotates from 45° (in the free field) to vertical, mostly within the area below the footing and around the granular.

As expected, the load displacement response (Figure 6) of the pile anchor for different diameters of the granular pile indicates that both pile resistance and stiffness increase with increasing pile diameter. However, while the stiffness increases steadily with the pile diameter, the pile size effect on resistance is more dramatic when the pile diameter increases from 0.25 m to 0.5 m than from 0.5 m to 1.0 m. Examination of the FEM results showed that this cannot be attributed to the resistance component induced by the pile weight; it is rather associated with the failure mechanism which extends outside the pile periphery and engages more soil zones as the diameter increased from 0.25 m to 0.5 m.

Figure 6 indicates that establishing the pile resistance response curve is critical in designing a GPAF system in order to determine the allowable uplift force that can be resisted by the system, the associated factor of safety (FOS) and allowable heave. For example, it can be inferred from Figure 6 that the significant increase in the pile stiffness with increasing pile diameter could have an adverse effect on the efficiency of the GPAF system. This observation is further illustrated in Figure 7, which shows that as the pile diameter increases, the FOS that corresponds to a particular heave level can reduce significantly. The relatively low displacement required to mobilize the full strength of the granular pile system commensurates with the behaviour of conventional, frictional piles that derive their resistance from only skin friction or adhesion.

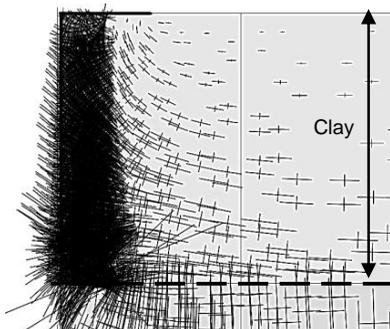


Figure 5. Rotation of Principal Stresses Around Granular Pile

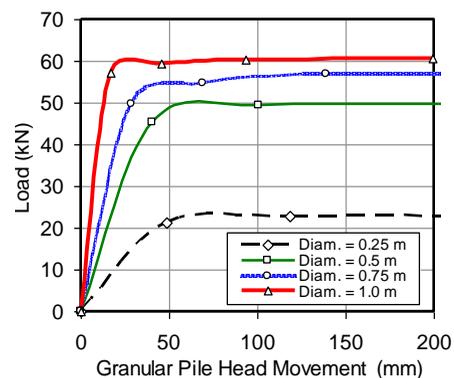


Figure 6. Load Displacement Curve of Pile Anchor

4.2 Behaviour of a Single Pile under a Shrinkage Event

Previous investigations found in the literature did not address the suitability of the GPAF system to resist shrinkage events when reactive soil loses moisture. However, it can be readily shown that under such event the granular pile will be subjected to compressive force, which may lead to bulging into the surrounding reactive soil, resulting in either failure of the foundation system or excessive settlement. This may also be associated with possible buckling of the pile anchor, which will be subjected to a compressive force if rigidly connected to the foundation element.

In order to enable the GPAF system to resist shrinkage, it is proposed that the granular pile is encased in a geofabric to reinforce the pile by providing hoop resistance during a shrinkage event. To the authors' best knowledge, geofabric was never tried with the GPAF systems, although it has been used as a reinforcement element of stone columns constructed in soft clays [e.g., 14, 15].

The effect of geofabric on resistance to shrinkage of the reactive clay investigated in this study was explored using the same 2D axi-symmetric model used for the heave analysis. The geofabric case was modelled using the geotextile element in PLAXIS, and different axial stiffness values were investigated. Both the efficiency of the geofabric and influence of its axial stiffness on arresting shrinkage under the modelled footing are evident from the settlement curve of Figure 8. For example, the case of $EA_{(Geofabric)} = 2000 \text{ kN/m}$ reduced the settlement by about 55%, compared with the case of no fabric. Similarly, the successful role of the geofabric in reducing bulging of the granular pile significantly is demonstrated in Figure 9, which shows variation of the lateral movement along the horizontal line passing through mid height of the granular pile.

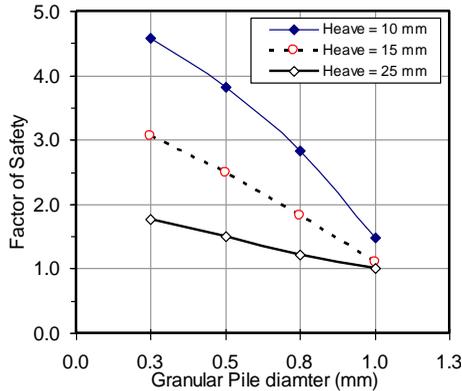


Figure 7. FOS at different heave levels

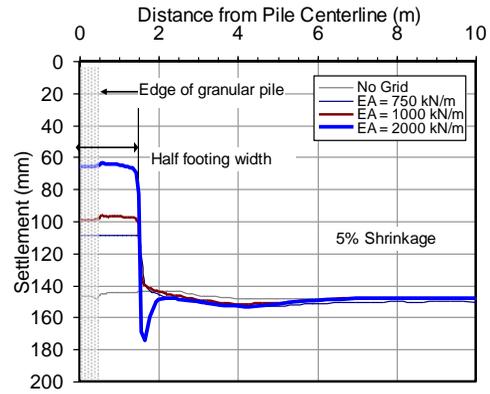


Figure 8. Settlement trough during a shrinkage event

4.3 Effect of Pile Group

The effect of group action on the efficiency of the GPAF system is illustrated in Figure 10 in terms of surface heave for pile spacing of $2d$, $3d$ and $4d$, compared with the response of a single pile. It is clear from the figure that the efficiency can be reduced significantly by pile group action (from an average of 92% for a single pile to about 70% for all pile groups). However, the exact pile spacing within the $2d$ to $4d$ range did not seem to have a significant effect on the pile group efficiency. These results are ostensibly promising, since it can reduce the cost of construction by reducing the number of piles and labour required to install the geofabric casing.

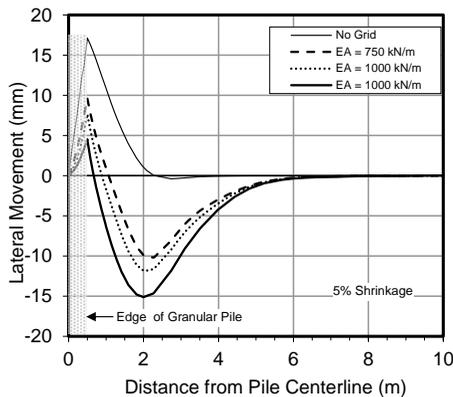


Figure 9. Effect of geofabric in reducing bulging of granular pile

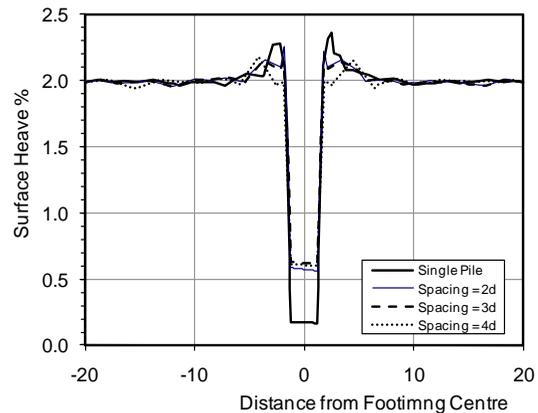


Figure 10. Effect of pile spacing on surface settlement

5. Summary and Conclusions

This paper presented results from FEM analyses of the granular pile-anchor foundation system (GPAF) as a plausible foundation solution in reactive soils. The paper proposed modification to the system to enable

resistance to both heave and shrinkage by encasing the granular pile into a geofabric tube. The analysis focused on the behaviour of a single pile under both heave and shrinkage event.

The analyses confirm the potential of the GPAF system and indicate that the resistance to both heave and shrinkage can improve dramatically. However, success of the technique in real applications requires reasonable prediction of the load-displacement curve of the pile anchor. The results also show that one critical limitation of the system may result from the fact that mobilization of the full skin resistance of the pile soil interface requires only small deformation. Further studies are required to explore this limitation whilst consider working loads applied to foundations as well as pile group effect. The analyses also show that using a group of piles instead of a single pile under a footing can reduce the efficiency of the GPAF system.

6. References

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