Three-Dimensional Numerical Modelling of Geosynthetic Reinforced Pile-Supported Embankments over Soft Ground

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ABSTRACT

Construction of embankments over soft ground is a challenging task for geotechnical engineers. This is mainly due to the undesirable characteristics of soft soil such as low bearing capacity, insufficient shear strength and very high compressibility which can result in bearing failure, large settlements and local or global instability. Geosynthetic reinforced pile-supported (GRPS) embankments provide an effective solution to overcome these issues. With the use of this technique a higher portion of the embankment load can be transferred to the piles rather than the soft foundation soil, thus reducing the stresses applied on to the soft soil. The performance of a GRPS embankment can vary with different parameters such as pile spacing, pile diameter, stiffness of the geosynthetic layer, elastic modulus of the piles and height of the embankment. This study presents the results of a parametric study using the finite element modelling to investigate the behaviour of a GRPS embankment. Three-dimensional numerical modelling is carried out considering two rows of piles to investigate both longitudinal and transverse load transfer mechanisms. The variation of maximum settlement at the crest of the embankment, tension in the geosynthetic layer and the stress concentration ratio with the earlier mentioned parameters are discussed in the paper.

Keywords: finite element modelling, GRPS embankment, parametric study, soft soil, stress concentration ratio

1 INTRODUCTION

Due to the rapid growth of world population, suitable land for construction is being reduced drastically. Construction of embankments on soft foundation soils has increased considerably over the past few years with the increasing number of infrastructure development projects. Geotechnical engineers when dealing with embankment construction on soft soils, face many difficulties, some of which are premature failure of the embankment, large settlements over a long period of time and large lateral displacements. These problems are a result of the undesirable characteristics of soft soils such as insufficient shear strength, high compressibility and low bearing capacity. For this reason, improvement of soft ground before any construction is undertaken on that is essential.

Various ground improvement techniques can be found in the literature for this purpose (Mitchell 1981; Magnan 1994; Shen et al. 2005). Preloading, constructing in stages, reducing the embankment slope, adding vertical drains and introducing column supports are some of them. The addition of columns will provide support to the embankment thus reducing the load transferred to the soft soil and reducing both vertical and lateral settlements (Han and Akins 2002; Pham et al. 2004; Stewart et al. 2004; Huang et al. 2009). These column supports can be concrete piles, deep mixed columns, aggregate piers or stone columns. A layer of geosynthetic reinforcement can be introduced on top of the columns in order to enhance the load transfer from the embankment to the piles (Han and Gabr 2002; Collin 2003; Qian and Ling 2009). This study is focused on geosynthetic reinforced pile-supported embankments constructed on soft foundation soils.

Both experimental and numerical studies can be used to evaluate the performance of a GRPS embankment system. However, when compared to experimental studies, numerical studies can be efficient, cost effective, easy to conduct and also more suitable to observe the behaviour in the serviceability conditions. A large number of studies with two-dimensional numerical modelling have been carried out in the past but only a few three-dimensional numerical studies can be found. This is because three-dimensional modelling is much more complex, time consuming and require more expensive resources such as high performance computers. This paper presents a three-dimensional parametric study performed on a typical GRPS embankment constructed on a soft foundation soil. Pile spacing, pile diameter, elastic modulus of the piles, stiffness of the geosynthetic layer and the height of the embankment are changed and the behaviour of the embankment is observed during the construction period and serviceability period. ABAQUS/Standard finite element modelling software was used for the three dimensional numerical modelling.

2 NUMERICAL ANALYSIS

The embankment problem used for the analysis is shown in Figure 1 (not to scale). This is the baseline case used for the parametric study. The embankment has a height of 4.5 m, a crest width of 24 m and the slope is 1:2 (vertical:horizontal). The topmost soil layer is a 1 m thick coarse grained fill layer and below that is a 14 m thick soft clay layer. The soil layer below the soft clay layer is assumed to be a firm bearing layer. The embankment is supported on piles which are 15 m long and 0.7 m in diameter and the centre to centre pile spacing is 3 m. The ground water table (GWT) is at a depth of 1 m below the ground surface. The geosynthetic layer was sandwiched between two 0.25 m thick gravel layers to prevent damage during construction. The embankment was constructed over 55 days and left for consolidation for 125 days. The rate of construction was not changed during the parametric study.

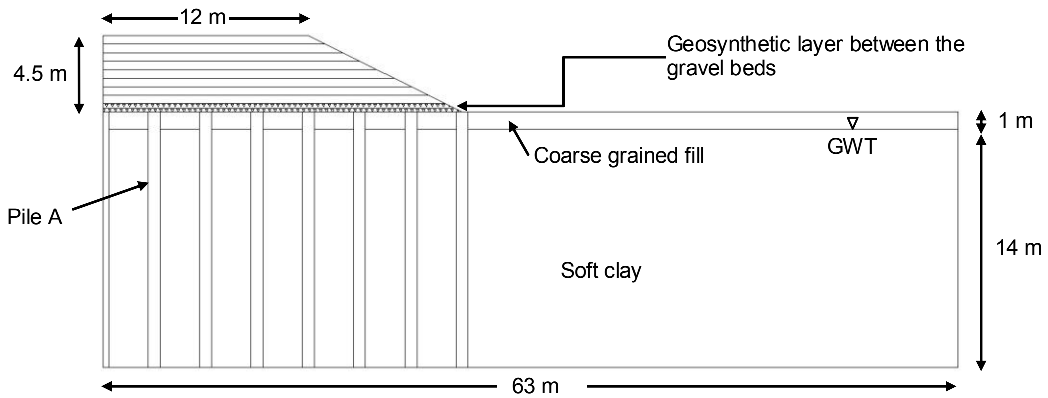


Figure 1. Cross section of the embankment with soil profile

Due to the symmetry of the embankment, only a half of the embankment is modelled considering a 6 m wide section with two pile rows. The horizontal length of the model is taken to be 63 m, which is three times the base length, in order to minimise the boundary effects. The bottom boundary (z=0 plane) was fixed in all directions and the left hand side boundary (x=0 plane) was assigned with a symmetrical boundary condition. The far end (x=63 plane) was fixed only in the x direction and the vertical planes (y=0 and y=6) were also assigned with symmetrical boundary conditions. Pore water was only allowed to drain through the top surface of the soft clay layer. The geosynthetic layer was modelled using eight-node membrane elements and the other parts are modelled using twenty-node brick elements.

2.1 Material model and parameters

Material parameters found in literature are used in the numerical simulations as shown in Table 1. The soft clay layer was modelled using the Modified Cam Clay (MCC) model where λ is the slope of the virgin consolidation line; κ is the slope of the swelling line; e_1 is the void ratio at unit pressure; M is the slope of the critical state line and ν is the Poisson's ratio.

Table 1: Material properties used in the baseline case

Material	Parameters
Coarse grained fill	E = 7 MPa, c' = 15 kPa, φ' = 28^0, ψ = 0^0, ν = 0.3, γ = 20 kN/m^3
Soft clay	λ = 0.15, κ = 0.03, M = 0.95, e_1= 1.79, ν = 0.4, k = 4.32x10^{-4} m/day, γ = 17 kN/m^3
Embankment fill	E = 20 MPa, c' = 10 kPa, φ' = 30^0, ψ = 0^0, ν = 0.3, γ = 18.5 kN/m^3
Gravel bed	E = 20 MPa, c' = 10 kPa, φ' = 40^0, ψ = 0^0, ν = 0.3, γ = 18.5 kN/m^3
Piles	E = 20 GPa, ν = 0.2
Geosynthetic	J =Et = 1180 kN/m, ν = 0.3, t = 10 mm

J – Stiffness of the geosynthetic, t – thickness of the geosynthetic, γ – unit weight of soil

A linear elastic-perfectly plastic model with Mohr-Coulomb failure criterion was used to model the embankment fill, coarse grained fill and the gravel beds. The parameters used for this model are effective cohesion, c', friction angle, φ', dilation angle, ψ, Young's modulus, E and Poisson's ratio, v. The geosynthetic layer and piles were modelled as linear elastic materials. Interface friction is considered between the gravel bed and the geosynthetic layer assuming an interface friction coefficient of 0.8.

2.2 Variables and their values used in the parametric study

The variables used for the parametric study are pile spacing, pile diameter, elastic modulus of piles, stiffness of the geosynthetic layer and the height of the embankment. Only one parameter was changed at a time while keeping the other parameters at the baseline case values. The details are summarised in Table 2.

Table 2: Values used in the parametric study

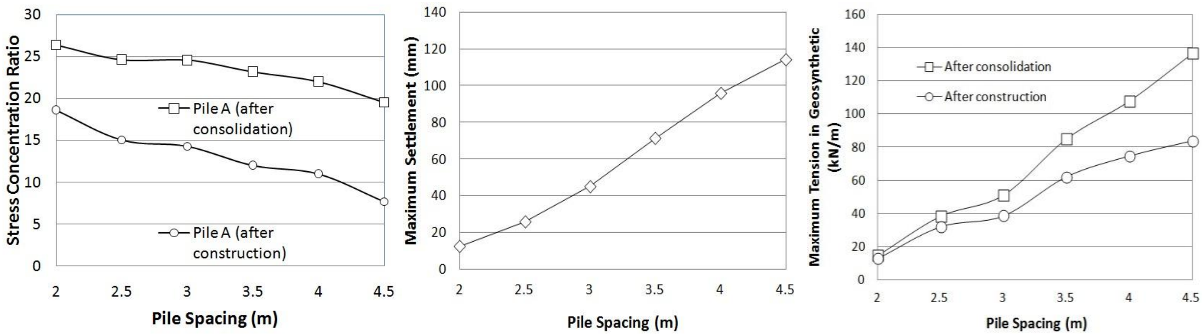
Parameter	Values
Pile spacing (m)	2.0, 2.5, 3.0, 3.5, 4.0, 4.5
Pile diameter (m)	0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1
Elastic modulus of piles (MPa)	50, 100, 1000, 20000
Stiffness of the geosynthetic (kN/m)	50, 500, 5000, 10000, 20000
Embankment height (m)	1, 1.5, 2.5, 3.5, 4.5

3 ANALYSIS OF RESULTS

The results obtained by the parametric study are presented in this section. Three main parameters were observed and they are stress concentration ratio (SCR), maximum settlement at the crest of the embankment at the end of consolidation and the maximum tension developed in the geosynthetic layer. Among these parameters SCR can be used to quantify the load transfer mechanism and it is defined as the ratio of vertical stress on piles to the vertical stress on surrounding foundation soil. In this study pile A which is shown in Figure 1, is selected for the calculation of SCR. The maximum settlement at the crest of the embankment is selected for observation because that is the settlement we are interested in at the end. The tension in the geosynthetic layer is not uniform along the length. However, for design purposes, the maximum tension developed in the geosynthetic layer is of more interest to the practitioners.

3.1 Pile spacing

The variation of observing parameters against pile spacing is shown in Figure 2.



(a) (b) (c)

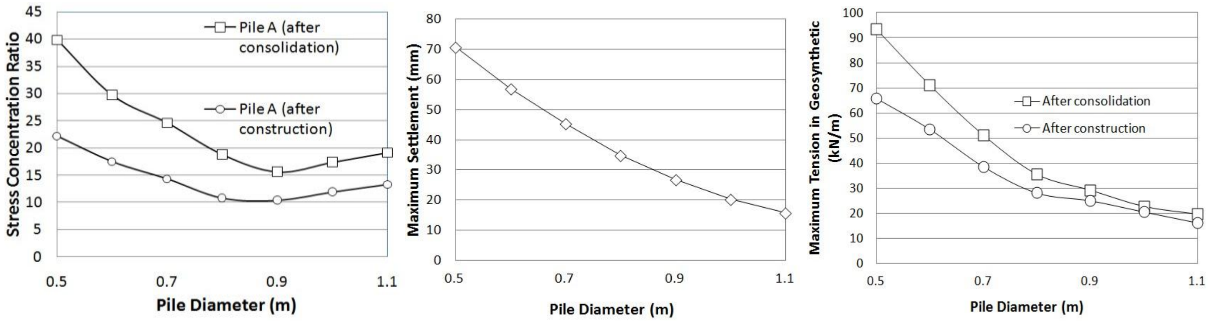
Figure 2. (a) SCR vs pile spacing (b) Maximum settlement at the embankment crest vs pile spacing (c) Maximum tension in the geosynthetic layer vs pile spacing.

Out of the three graphs, Figure 2(a) shows the variation of stress concentration ratio on pile A. The bottom line represents the SCR values just after construction of the embankment and the top line represents the SCR values at the end of 125 days consolidation period. It is clearly visible that the SCR value after consolidation always remains greater than the SCR value at the end of construction. This is because during the period of consolidation, foundation soil will settle and this will result in further development of soil arches inside the embankment fill. As a result, more load will be transferred to the piles, thus increasing the stress concentration ratio. Both lines show a downward variation of SCR with increasing pile spacing. The reason for that is when the pile spacing is large, soil arches become unstable and the load transferred to the piles by soil arching is reduced and the SCR value is decreased as a result. Since the load transferred to the piles is reducing with increasing pile spacing, the load transferred to the foundation soil will increase; this will increase the settlement of the embankment as shown in Figure 2(b). Pile spacing has a significant influence on the settlement. When the pile spacing is increased from 2 m to 4.5 m, the settlement has increased by more than seven times. With increasing pile spacing, the differential settlement in the embankment will increase and this will cause the strain in the geosynthetic layer to increase, thus increasing the tension developed as shown in Figure 2(c). The tension in the geosynthetic layer after consolidation is always higher than the tension just after construction.

3.2 Pile diameter

According to Figure 3(a), the SCR value initially decreases with the pile diameter and then starts to increase. When pile diameter is increasing the stress on the pile will reduce even though more load is transferred to the pile. Therefore, the SCR value will gradually reduce. But after some point the stress on soft soil will start to reduce because the plan area covered by the foundation soil will decrease with increasing diameter. Due to this reduction in the stress on foundation soil, the SCR value will start to increase.

The load transferred to the piles will increase with increasing pile diameter and the plan area of the foundation soil will reduce. Therefore, the portion of embankment fill supported by the foundation soil (in between piles) will also reduce. These reasons will cause a reduction of the load transferred to the foundation soil and reduce the settlements as shown in Figure 3(b). The tension in the geosynthetic layer will reduce as can be seen in Figure 3(c) because more load is taken by piles rather than the geosynthetic layer.

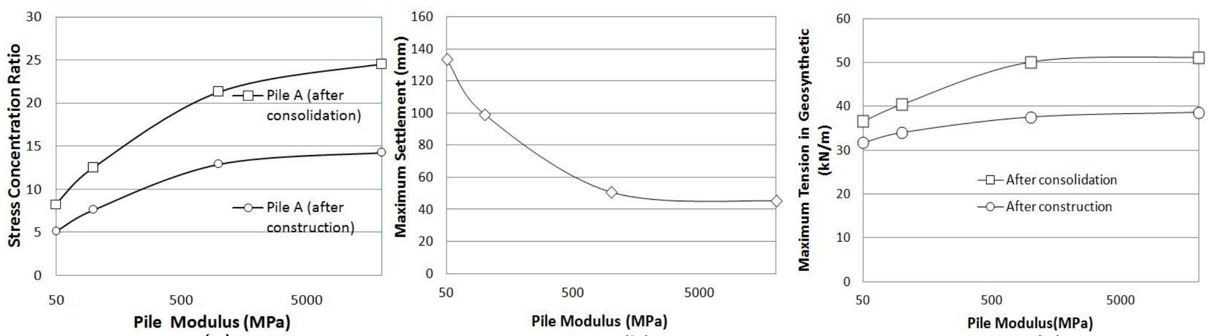


(a) (b) (c)

Figure 3. (a) SCR vs pile diameter (b) Maximum settlement at the embankment crest vs pile diameter (c) Maximum tension in the geosynthetic layer vs pile diameter

3.3 Elastic modulus of piles

Figure 4 shows the variation of stress concentration ratio, maximum settlement of the embankment crest and the maximum tension in the geosynthetic layer against the elastic modulus of piles.



(a) (b) (c)

Figure 4. (a) SCR vs elastic modulus of piles (b) Maximum settlement at the embankment crest vs elastic modulus of piles (c) Maximum tension in the geosynthetic layer vs elastic modulus of piles

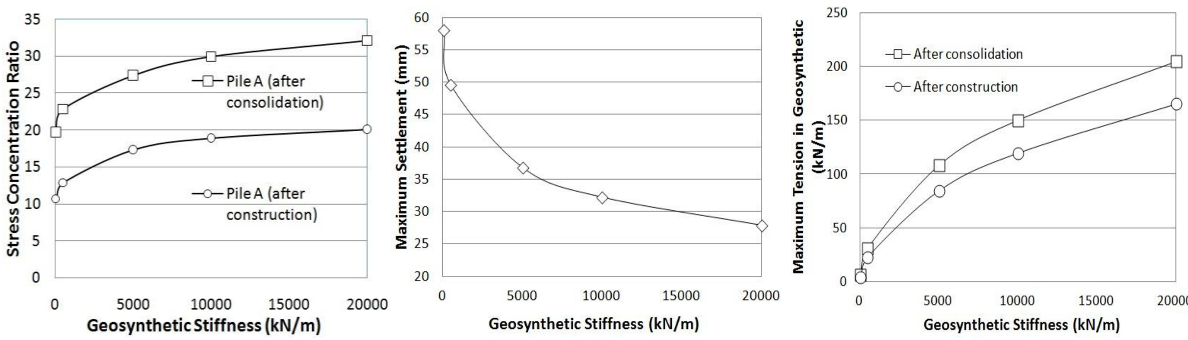
According to Figure 4(a), when the elastic modulus of piles is increasing, the SCR value is also increasing. Soil arching is not the only factor contributing to the load transfer mechanism. The stress concentration due to the stiffness difference between piles and surrounding soft soil is also an important factor for the load transfer in a pile-supported embankment. When this stiffness difference is higher, more load is transferred to the piles. But when the pile modulus is approaching a very high value, the improvement is becoming less significant. This fact is common for both maximum settlement and tension in the geosynthetic layer as shown in Figures 4(b) and 4(c) respectively.

3.4 Stiffness of the geosynthetic layer

The tensile stiffness is a very important material property for a geosynthetic layer. It can vary depending on the type of geosynthetic used. Although it is a very important factor, its influence has not been taken into account in any of the currently available design methods for GRPS embankments. According to Figure 5(a), the SCR value is considerably improving with increasing geosynthetic stiffness at lower stiffness values. This is because the increasing geosynthetic stiffness will make the reinforced earth platform stiffer and promote stress transfer from embankment to the piles while reducing the differential settlements. However, at very high stiffness values, the improvement is not that significant. When the stiffness of the geosynthetic layer is increased, soil arching will reduce because the differential settlements are lower. Therefore, the rate of improvement of the SCR value will gradually decrease.

Figure 5(b) shows the variation of maximum settlement at the crest of the embankment with geosynthetic stiffness. When the stiffness of the reinforced earth platform is increased with the increasing geosynthetic stiffness, the load transferred to the foundation soil will reduce and this will result in lower settlement values at the base as well as the crest of the embankment. At lower values of geosynthetic stiffness, the settlement improvement is significant due to the enhanced load transfer to the piles. However, at very high stiffness values, the rate of improvement gradually reduces similar to the stress concentration ratio.

The tension in the geosynthetic layer is increasing with the stiffness as shown in Figure 5(c). This is because the tension of the geosynthetic is the product of strain and its tensile stiffness. The maximum tension can be always found near the pile edges. This is because the highest differential settlements occur near the pile edges and therefore the strain in the geosynthetic layer is highest in that area.

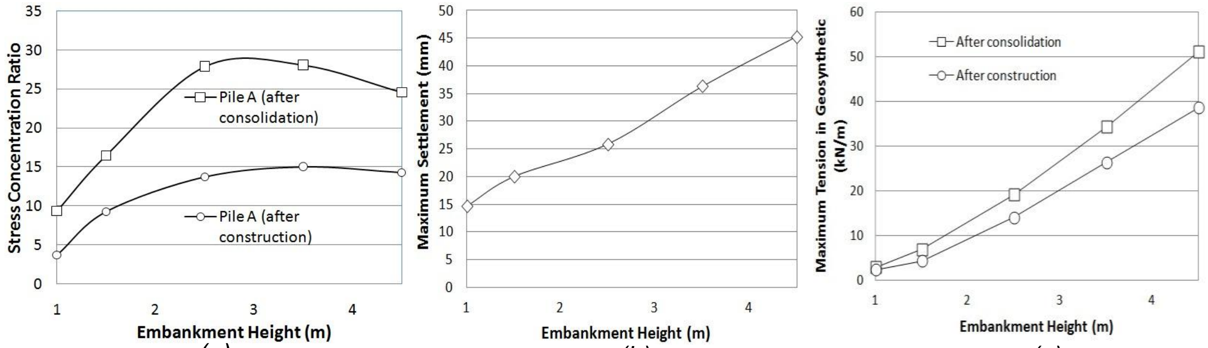


(a) (b) (c)

Figure 5. (a) SCR vs geosynthetic stiffness (b) Maximum settlement at the embankment crest vs geosynthetic stiffness (c) Maximum tension in the geosynthetic layer vs geosynthetic stiffness

3.5 Height of the embankment

The variation of stress concentration ratio is plotted against the height of the embankment in Figure 6(a). At first, the SCR value is increasing with increasing embankment height. This is because at lower embankment heights there is not enough fill height to develop proper soil arches. As a result, very low SCR values can be observed for lower embankment heights. However, as the embankment height increases soil arches develop inside the embankment fill and more load is transferred to the piles, thus increasing the stress concentration ratio. It can be seen that after a certain height the SCR value starts reducing. Even though soil arches are developed inside the embankment, they might not be stable at large embankment heights because those arches are not solid arches. Therefore, when the height of the embankment is kept increasing, at some point the arches will become unstable and the load transferred to the piles will reduce and the SCR will reduce along with that. According to Figure 6(b), the maximum settlement at the embankment crest is increasing with the embankment height as expected because the load applied on to the foundation soil will increase with the height of the embankment. As a result of increasing total and differential settlements, the tension in the geosynthetic layer will also increase as shown in Figure 6(c).



(a) *(b)* *(c)*

Figure 6. (a) SCR vs embankment height (b) Maximum settlement at the embankment crest vs embankment height (c) Maximum tension in the geosynthetic layer vs embankment height

4 CONCLUSION

A three-dimensional parametric study was carried out on a GRPS embankment and the results are presented in this study. The results are expected to be more accurate because three-dimensional models simulate the actual field condition much better than two-dimensional plane strain models. Pile spacing, pile diameter, elastic modulus of piles, stiffness of the geosynthetic layer and the height of the embankment were varied and the behaviour of the embankment was assessed using the stress concentration ratio, maximum settlement at the embankment crest and the maximum tension developed in the geosynthetic layer. Results show the variation of these parameters and having a knowledge about the variation patterns can be extremely helpful for the geotechnical engineers dealing with GRPS embankment design. Further studies have to be carried out to investigate the inter-relationships between the varying parameters because in this study the parameters were only varied individually.

5 ACKNOWLEDGEMENTS

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