Three Dimensional Finite Element Analysis of Geogrid Reinforced Piled Embankments on Soft Clay

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ABSTRACT: This paper presents the results of three-dimensional (3-D) finite element analysis of a monitored geogrids-reinforced embankment constructed on soft clay formation and supported by cast in-situ piles. The analyses were conducted using the software PLAXIS 3D. A comparison between the predicted and monitored responses is presented to assess the adequacy of the adopted numerical model. The model was used in a parametric study to investigate the effect of key aspects of the embankment on the efficiency of the piled embankment. Moreover, a comparison was performed between the results of the 3-D analyses and the analytical solutions. This paper concluded that the effect of using pile caps decreased both the total and differential settlement and increased the efficiency of the piled embankment system. The study of using geogrids revealed that it can contribute to decreasing the settlement and maximizing the part of the embankment load transferred to piles. Moreover it was found that increasing the stiffness of the geogrids provided higher values of tensile forces, and hence has more influence on the embankment loads carried by piles rather than using multiple layers with lower stiffness. The efficiency of the piled embankments system was also found to be greater when higher embankments are used rather than the low height embankments. The comparison between the numerical (3-D) model and the theoretical design methods revealed that many analytical solutions are non-accurate compared to the (3-D) finite element numerical.

Keywords: Efficiency, Embankment, Geogrids, Soft clay.

1 INTRODUCTION

The spreading of construction to extend to areas that are unfavorable for construction purposes resulted in encountering problematic soil conditions. The need to improve the problematic ground conditions in order to make it suitable for construction purposes poses challenges to the design and construction engineers. Accordingly, the development of techniques to accomplish this goal is of vital importance for the civilization growth. With the increasing advances in construction, many techniques have been used to overcome the engineering problems facing construction on soft / very soft clay formations. These problems are due to the characteristics of such formation; mainly low shear strength, low permeability and high compressibility.

The Geogrid-Reinforced Pile-Supported Embankments is one of the techniques used worldwide for soft clay stabilization. The basic concept of this method is to install piles with a certain grid formation in a soft soil down to a certain depth, which generally reaches a firm stratum. The geosynthetic material is placed between the embankment and piles to increase the efficiency of load transfer to the piles. The main purposes of using the Geogrid Reinforced Pile Supported Embankments technique, especially for road and railway embankments, are to reduce the total and differential settlements, reduce lateral displacements and increase the stability of different urban infra-structures. Moreover, this technique can be used when time is of a major concern in urgent projects such as road widening projects. Pile supported earth embankments have been used with or without geogrid reinforcements. The geogrid materials are laid on top of a thin layer of embankment materials. After constructing the geogrid layers, the embankment fill is built up to the required height.

Many numerical and field studies have been reported in the litrature to investigate the stress distribution, load transfer mechanism and other major parameters in the piled embankments including Han and Gabr (2002), Sovulj et al. (2005), Almeida et al. (2007), Collins et al. (2007), Jenck et al.(2009) and Van Eeklen et al. (2011).

This study numerically investigates the performance of a monitored earth embankment reported by Liu et.al. (2007) that was constructed on a very soft to soft clay formation and stabilized by cast in-situ piles. Numerical analyses were carried out considering three-dimensional (3-D) numerical idealization of the system. A comparison is conducted between the monitored and the predicted responses to validate the numerical model. An extensive sensitivity study was carried out on the validated embankment model to explore the influence of major characteristics of the piled embankments which may be of concern when designing such embankments. The considered parameters included the stiffness of the geogrid used for embankment reinforcement compared to the effect of using multi-layers of geogrid, the effect of using pile caps under the reinforced piled embankments and the effect of changing embankment height.

The efficiency of the piled embankment system, which is defined as the percentage of loads transferred to the piles to the total load of the embankment, is considered through this study. Additionally, the results of three dimensional numerical model by PLAXIS 3D is compared to results of empirical equations adopted by different codes/guidelines for estimating the efficiency of the piled embankment.

2 NUMERICAL MODELLING OF A MONITORED PILED EMBANKMENT

The earth embankment at a northern suburb of Shanghai, China, as reported by Liu et.al. (2007) was considered in the current numerical study. The embankment was 5.6 m high and 120 m long and the crown width was about 35 m. The embankment side slopes were 1 V to 1.5 H. A cross-section view of the monitored piled embankment is shown in Figure 1.

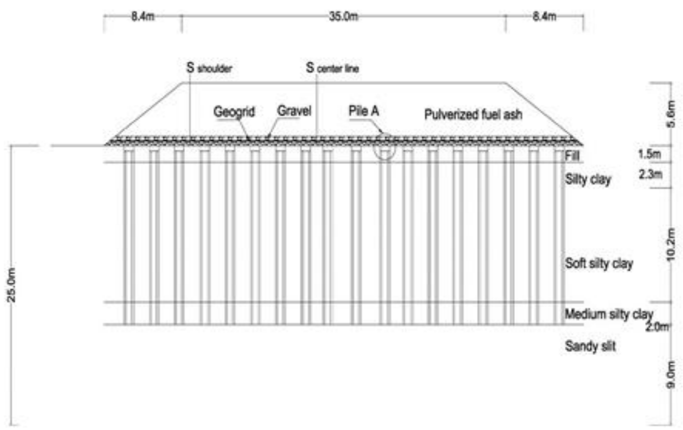

Figure 1. Configuration of the monitored piled embankment (after Liu et.al., 2007)

The embankment is supported by cast in-situ annulus concrete piles with length of 16 m and founded on dense silty sand layer. The outer diameter of each pile was 1.008 m and the thickness of the concrete annulus was 120 mm. The annulus concrete piles were constructed in a square pattern at a distance of 3 m center to center and the overall area ratio of the piles was about 8.7%. One layer of biaxial polypropylene grid was installed between two 0.25 m thick gravel layers on top of the piles. The ultimate tensile strength in both longitudinal and transverse directions of the geogrid is 90 kN/m at a nominal tensile strain of 8%.
The subsurface soil formation at the site consist of a 1.5 m thick coarse grained fill overlying a 2.3 m thick deposit of silty clay; this deposit overlies soft clay that is approximately 10.2 m thick. The soft clay is underlain by a medium silty clay layer that is approximately 2 m thick followed by a sandy silt layer. The ground water level was at a depth of 1.5 m from the natural ground level. The construction of the embankment was carried out in nine lifts at overall duration of 55 days. The staged construction history was adopted in the verification numerical analyses carried out in this study.

Numerical analyses were carried out using the three dimensional finite element program PLAXIS 3D considering Ten Node elements were used in all the finite element calculations. Figure 2 shows the finite-element geometric model used in the analyses. The horizontal length of the finite-element mesh is 77.7 m, which is three times the width of half the embankment base so that the boundary effect can be minimized. Ten node elements were adopted in all finite element analyses.

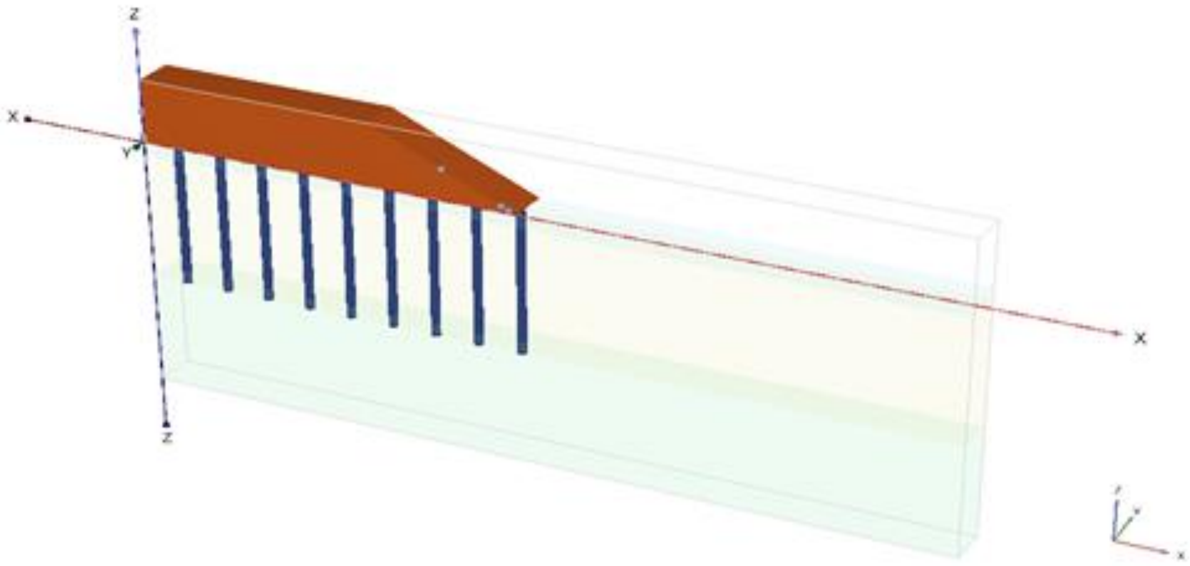

Figure 2. Three-dimensional model of the case study by PLAXIS 3D

The embankment fill material, the gravel cushion and the coarse grained fill layer are numerically modelled using the conventional Mohr-Coulomb (MC) model, while silty clay, soft clay, medium silty clay and the sandy silt layer were modelled using the Hardening Soil model (HS). The HS model is a non-linear elastoplastic material model capable of modeling soil non-linearity and stress dependency of soil stiffness.

The concrete piles are modelled using a linear elastic model. This assumption is adequate for the serviceability conditions analyzed herein. The pile has a Young’s modulus of 20 GPa and a Poisson’s ratio of 0.2.

Plastic loading analysis is carried out to model the embankment construction followed by consolidation analysis to estimate the long term deformations of the embankment and underlying formations. Table 1 presents a summary of the parameters that were adopted in the numerical analysis.

Table 1. Material properties adopted in the numerical analyses

Material	Embank-ment	Fill	Silty Clay	Soft Silty Clay	Medium Silty Clay	Sandy Silt
Model	MC	MC	HS	HS	HS	HS
C' (kPa)	10	15	5	3	10	15
Ø'	30	28	25	20	25	28
E (Mpa)	30	7	-	-	-	-
ν	0.3	0.3	0.35	0.4	0.35	0.35
E_0 (Mpa)	-	-	3	1.5	7	10
E_{ur}(Mpa)	-	-	9	4.5	21	30
m	-	-	0.8	1	0.8	0.5
k x 10^{-4} (m/day)	-	-	5	1	3	40

According to Liu et al. (2007), various instruments were installed in site to verify the design assumptions and to monitor the performance of the embankment. The installed instruments included surface settlement plates. The settlement plates were installed at two critical locations along the embankment profile. One plate (S centerline) was installed at the center line of the embankment on the surrounding soil and the other was located near the shoulder of the embankment (S shoulder).

The construction phases that were defined in the PLAXIS 3D finite element model are as follows:

Phase 1: Installation of piles.

Phases 2 to 10: Construction on embankment on nine lifts over 55 days (embankment construction time at site).

Phase 11: Consolidation analysis up to 180 days (the monitored time period at site)

The values of settlement resulted from the monitoring plan at site are compared to the output of the three-dimensional model performed using PLAXIS 3D at the center line and the shoulder of the embankment as shown in Figures 3 and 4, respectively.

The tensile force of the geogrid was also computed for this case study by ABAQUS model at location near to pile A. The average value of the tension force in the ABAQUS model was about 13.5 KN/m', while the value computed by PLAXIS 3D in this study revealed an average value of 13.2 KN/m'. Unfortunately, there is no available measured field data for the tensile forces in the geogrid.

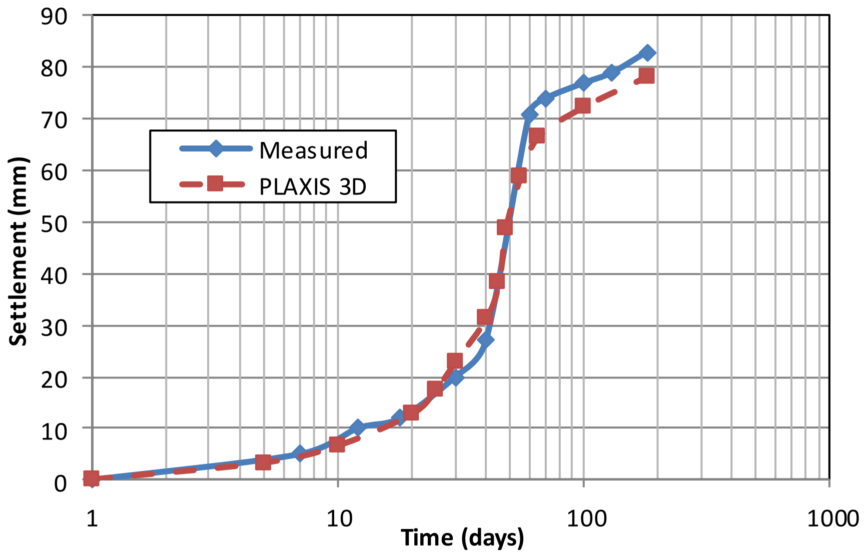

Figure 3. Deformation responses at the centerline of the verification embankment

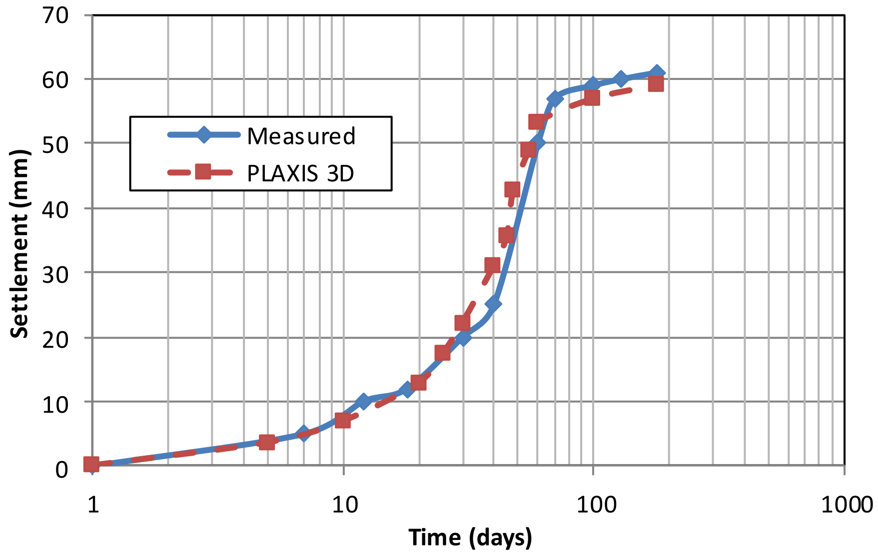

Figure 4. Deformation responses at the shoulder of the verification embankment

3 NUMERICAL ANALYSES AND SENSITIVITY STUDY

In order to investigate the influence of some parameters that may be of a noticeable impact on the behavior of the geogrid reinforced piled embankments, a numerical sensitivity study was carried out for the adopted case. The considered parameters are the geogrids stiffness used for embankment reinforcement, effect of using multiple layers of geogrid, effect of using pile caps under the reinforced piled embankments, and effect of changing embankment height.

A series of scenarios were analyzed in order to evaluate the effect of these parameters individually on the embankment response. There are many factors that can be highlighted in the proposed study such as the differential settlement, tension in the geogrid, stress concentration ratio and efficiency. However, this paper focuses on the efficiency to evaluate the response of the piled embankment systems.

3.1 *Effect of Changing Geogrid Properties and Number of Layers*

The inclusion of geogrid and its stiffness have influence on the performance of a piled embankment. The numerical analyses reveal that the inclusion of the geogrid layer reduces the maximum embankment settlements greatly. The maximum settlements at the pile head also decrease with the increase in the tensile stiffness of the geogrid. The values of the total and the differential settlement decrease by increasing the geogrid stiffness values as shown in Figure 5. However, the reduction in both total and differential settlements diminishes after a certain value of geogrid stiffness. This occurs because after a certain limit value of stiffness there is no further contribution induced by the geogrid to transmit additional loads to piles.

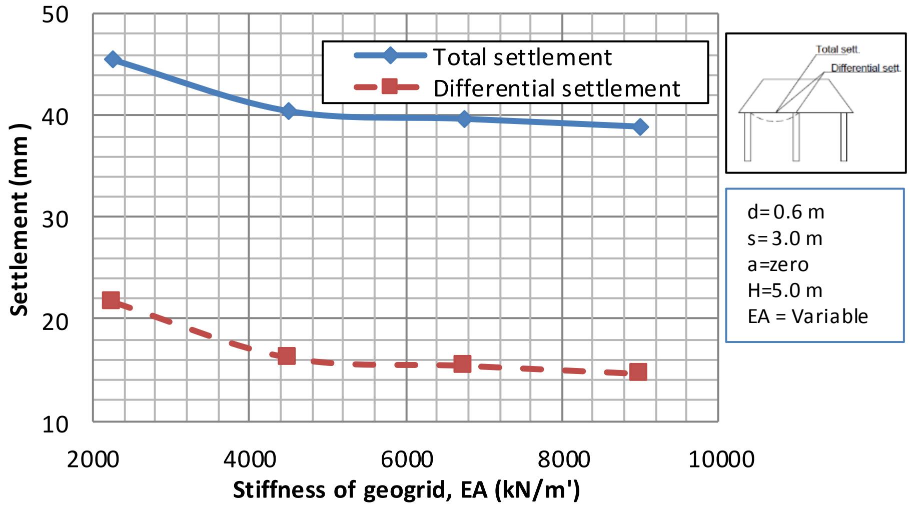

Figure 5. Effect of changing stiffness of the geogrids on the total and differential settlements

This is also verified by the results of the piled embankment efficiency shown in Figure 6. The conclusion that can be extracted from this study is that the geogrid layers transfers the load to the piles to a limited extent and after that the piles do not receive any additional embankment load even as the geogrid stiffness increase further. Moreover, increasing the stiffness of the geogrid maximized the efficiency of the piled embankment system only 10 % approximately through an increase for the geogrid stiffness about 400% (ie: geogrid stiffness increased from 2250 up to 9000 kN/m').

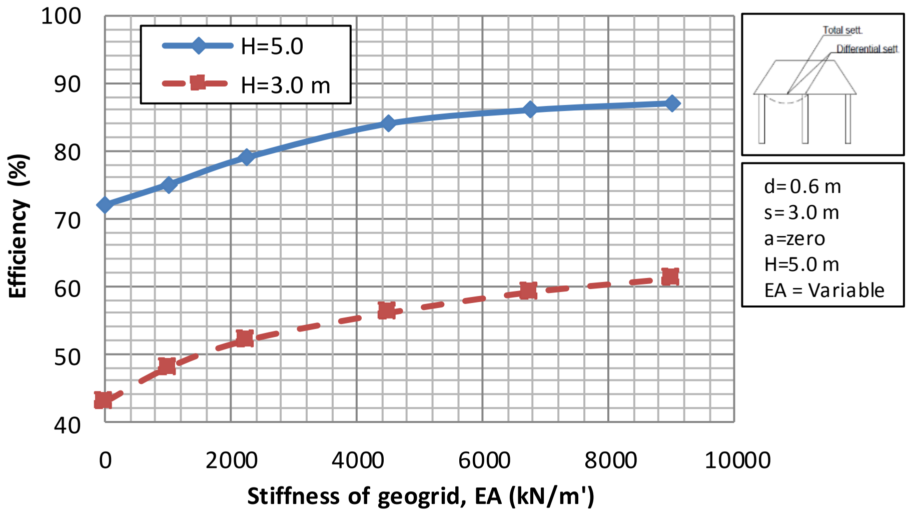

Figure 6. Effect of changing stiffness of the geogrids on efficiency of the piled embankment system

The factor of the geogrid reinforcement can be considered to provide a limited effect on the piled embankment behavior which is consistent with study carried out by Souvlj (2005). In that study, it was reported that the geogrid membrane does not seem to transfer significant load to the piles, hence there is no significant difference on the efficiency and the stress concentration ratio observed.

A comparison study was performed to compare the behavior of the piled embankment by using two adjacent geogrid layers to using only one layer with twice the stiffness of the geogrid and comparing using three layers to using triple the geogrid stiffness as shown in Figure 7.

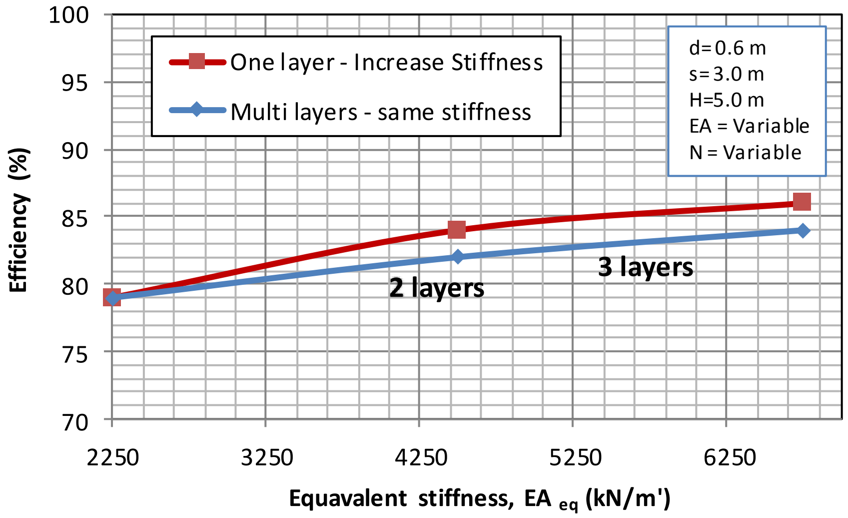

Figure 7. Comparison of efficiency when using multi-layers of geogrid to increase the stiffness

The effect of increasing the stiffness of the geogrids gives higher values of tensile forces and also resulted in higher percentage of embankment load carried by piles than using multiple layers and this is contradicting with study carried out by Sa et al. (2001) which concluded that the number of geogrids layers has more influence on the settlements and efficiency behavior than the values of the geogrids stiffness as long as the tensile stiffness is greater than approximately 1000 kN/m. On the other hand, it was found that the concept of adopting higher stiffness of the geogrids was adequate rather than increasing the number of layers as recommended by the British Standards.

3.2 *Effect of Embankment Height and the Critical Height Criteria*

The percentage of embankment load transferred to the piles is found to be highly affected by the increase in the height of the embankment. Figure 8 shows that the percentage of the embankment load transferred to the piles was very low at small heights of the embankments.

The numerical study revealed that efficiency was approximately 30% when the embankment height was only 2.0 m and started to increase due to increase of the embankment height to reach approximately 85 % corresponding to an embankment height of 7.0 m.

The British Standards justify the relationship between the embankment height and the efficiency of the piled embankments systems by adopting the critical height criteria (McGuire, 2011). It specified the critical height by applying a plane of equal settlement at which full soil arching occurs and consequently it recommends considering embankment heights greater than or equal to the critical height. The British standards limited the critical height of the embankment to be 1.4 times the clear spacing between piles.

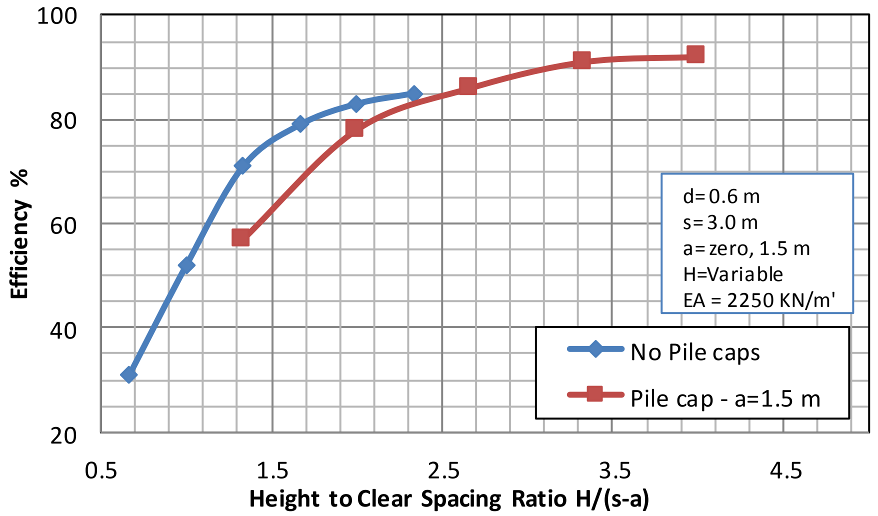

Figure 8. Effect of changing embankment height on the efficiency of the piled embankment

It has to be noted that the trend of the efficiency curve shown in Figure 8 shows higher rate of increase up to approximately the critical height recommended by British Standards. Beyond that height the rate tends to decrease.

3.3 *Effect of Using Pile Caps*

The influence of using pile caps under the piled embankment is considered in the parametric sensitivity study. The pile caps are assumed to be in square pattern and defined in terms of the width of cap (a), which is considered in the design equations adopted by British Standards. Based on the sensitivity study of the pile caps effect, it was concluded that increasing the width of the pile cap more than the limiting value will not have any significant effect on the load transferred to piles as shown in Figure 9 and consequently it will not effectively reduce the expected settlement and differential settlement values.

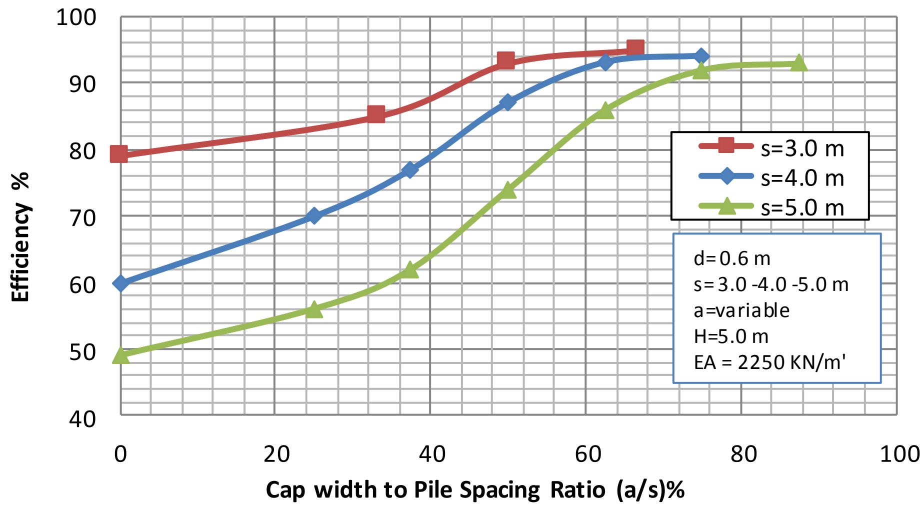

Figure 9. Effect of changing embankment height on the efficiency of the piled embankment

4 COMPARING THE RESULTS OF PLAXIS 3D TO THE COMPUTED RESULTS OF THE ANALYTICAL METHODS

The design of the geogrids-reinforced piled embankments is addressed by several analytical and empirical methods that can provide estimate the part of load carried by the piles of the piled embankment systems. In the current study, a comparison is conducted between the results of the 3D numerical model and those analytical methods. The values of loads transferred to the piles calculated using theoretical methods are compared with those computed using PLAXIS 3D as shown in Figure 10 using different embankments heights.

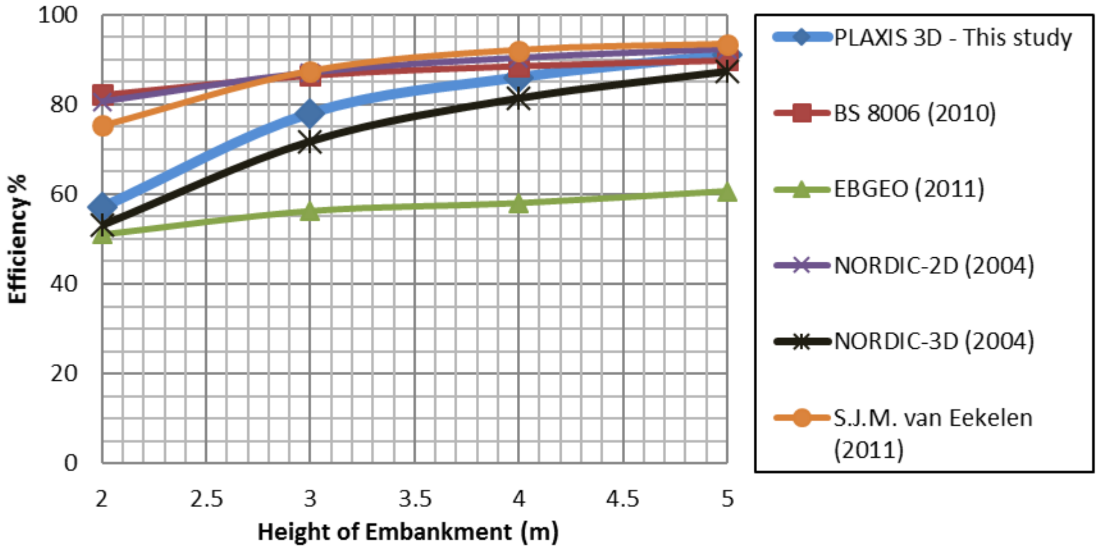

Figure 10. Comparison of the efficiency results between the PLAXIS 3D and different analytical methods

The computed values of efficiency using the Zaeske method adopted by EBGEO are found to be significantly lower than the values from PLAXIS 3D, and the difference tends to be higher with increasing embankment height. The calculated efficiency using the BS 8006, Van Eeklen (2011) and the Nordic 2D overestimated the efficiency at relatively low embankments. However, Svano et al. method that is adopted by Nordic 3D guidelines provided better agreement with the results of the PLAXIS 3D numerical model.

5 CONCLUSION

This study numerically investigates the performance of a monitored earth embankment that was constructed on a soft clay formation stabilized by cast in-situ piles. Numerical analyses were carried out considering three-dimensional (3-D) numerical idealization of the system. A good comparison is conducted between the monitored and the predicted responses. An extensive sensitivity study was carried out for this embankment to explore the influence of the parameters which may be of major concern on the efficiency of such embankments.

There are many parameters affect the behavior of the piled embankments of which this paper discussed the stiffness of the geogrid used for embankment reinforcement, the effect of using multiple layers of geogrid, the effect of changing embankment height and the effect of using mono-pile caps under the reinforced piled embankments.

Results of three dimensional numerical modeling using PLAXIS 3D are compared with measurements of the monitored embankment, and results of empirical equations adopted by the different codes/guidelines. Based on that study, the following conclusions can be drawn:

1) Three-dimensional numerical models can be adequately adopted to analyze piled embankments resting on soft clay formations.

2) Increasing the stiffness of the geogrids results in higher values of tensile forces and also results in more effective influence on the efficiency of the piles as compared with using multiple layers with lower geogrid stiffness. The inclusion of one layer of geogrid contributes to increase the efficiency of the piled embankment system about 15% to 25%.

3) The percentage of embankment loads transferred to piles increases with higher embankments rather than small height embankments and this verifies the critical height criteria recommended by British Standards BS8006-2010.

4) The efficiency of the piled embankment systems increases by enlarging the dimensions of the pile caps as it contributes to increase the embankment load that transfers directly to the piles via pile caps. Increasing the width of the pile cap can provide a significant effect up to a certain limit after which any additional increase in the cap size is not useful. This limit varies with the change of embankment height and pile cap spacing.

5) The efficiency of the piled embankments adopted by EBGEO is conservative compared to the numerical analysis. However, the efficiency calculated using the Nordic 3D method were found to be closer to the numerical results.

Notation

The following symbols are used in this paper:

A: Cross sectional area

a: Pile Cap Width

c‘: Effective cohesion

d: Pile diameter

E: Modulus of Elasticity

H: Embankment height

k: Coefficient of permeability

M: Slope of critical state line

N: Number of geogrid layers

S: Spacing between piles

υ: Poisson’s ratio

ϕ: Angle of Internal Friction

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