The performance of an embankment on soft ground reinforced with geosynthetic and floating pile walls system

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ABSTRACT: The design of embankments on soft ground requires the safety against potential bearing capacity failure, global slope instability, local failure, large total and/or differential settlements, and large lateral movement through the stages of embankment construction. Horizontal geogrid reinforcement combined with floating pile walls can provide an effective solution to ground improvement to support high embankments. This paper demonstrates the results of numerical analysis to study the performance of embankment on soft ground in the north coast of Egypt near Dumyat City, and the effect of inclusion of horizontal reinforcement of geogrid layer and vertical floating pile walls. The numerical results show that a combination of geogrid reinforcement and the floating pile walls is very effective for the improvement of soft ground and the stability of the embankment.

KEYWORDS: Geogrid Layer, Embankment, Floating Pile Wall Mechanism, Settlement, Numerical simulation.

1. INTRODUCTION

The design of high embankments on very soft soil ground normally requires the assessment of the following problems: bearing capacity failure, global slope failure, local instability, excessive lateral displacement, and in tolerable total and/or differential settlements (Long et al.1996; Ochiai et al. 1996; Han and Gabr 2002; Shukla and Kumar 2008) constructed on a soft and highly compressible deposit with low permeability, the issue of large time-dependent consolidation settlements warrants particular attention. A variety of techniques may be used to solve these problems, such as the use of lightweight fill, over-excavation and replacement by sand/gravels, vertical drains with preloading, horizontal reinforcement, and vertical reinforcement. In comparison with the 'reinforced with geosynthetic and pile walls' strategy, the use of lightweight fill is often costly for most projects. Over excavation and replacement by sand/gravels may be less expensive but often requires a large amount of earthworks and long construction duration. Vertical drains with preloading can be less expensive, but the construction duration can be long and the bearing capacity of soft ground may not be improved. In some instances, a combined application of horizontal and vertical reinforcement provides an economical and effective solution to soft ground improvement problems for construction of high embankments (Koerner 2000; Abdullah and Edil2007). Han and Gabr (2002) conducted two-dimensional axisymmetric analyses on pile–soil–geosynthetic interaction by considering a single pile and the surrounding soil as a unit cell. Borges (2004) analyzed the three-dimensional behavior of an embankment on soft soils incorporating vertical drains using a numerical model based on the finite element method. Deb et al. (2008) studied the behavior of multi-layer geosynthetic reinforced granular fill over stone column reinforced soft soil, and the Kelvin–Voight model was used to analyze the time-dependent behavior of saturated soft soil. Han et al. (2007) discussed the effect of the combined application of geosynthetic and columns in the widening of embankments. However, none of these studies fully considered the effect of the lateral movement of embankment. In the present study, a two-dimensional finite element analysis was used to study the performance of embankments on soft ground with different reinforcing conditions :(1) an unreinforced embankment, (2) an embankment reinforced with geogrid layer and (3) an embankment reinforced with both geogrid layer and floating pile walls.

2. NUMERICAL ANALYSIS

2.1 *The Case Study*

The case study selected for the numerical analysis is related to the construction of a highway embankment on soft ground as a part of the international highway in the Northern coast of Egypt from Dumyat harbor to Port Said City. The insitu soil consisted of four meter thickness of silty sand followed by soft clay layer of thickness twenty seven and half meter. The soft clay layer is underlain by dense silty sand layer. Based on CPT insitu tests, the soft clay layer had an over-consolidation ratios between 2 and 3. Ground water depth was encountered at depth 0.50 m below ground level. The embankment is 6.0 m height and 12 m crest width. The common practice in this area to reduce the settlement beneath the embankment is the implementation of preloading technique which requires a long time to improve the strength and deformation parameters of the insitu soft clay layer. In this case history, a sand cushion, 0.5 m thick, is placed at the bottom of the embankment and over the top of the insitu soil. Floating pile walls with geogrid layer combination are placed at the bottom of the sand cushion to reduce the settlement of the soft clay strata due to the embankment loads and enhance the stability of the embankment. Pile walls are 1.5 m thick and the typical center-to-center spacing between two pile walls is 3.0 m as shown in Figure (1). The pile walls are rows of tangential concrete piles with minimum steel reinforcement.

2.2 Finite *Element Model*

A two dimensional finite element model was established to simulate the design of the embankment supporting system as shown in Figure (1).

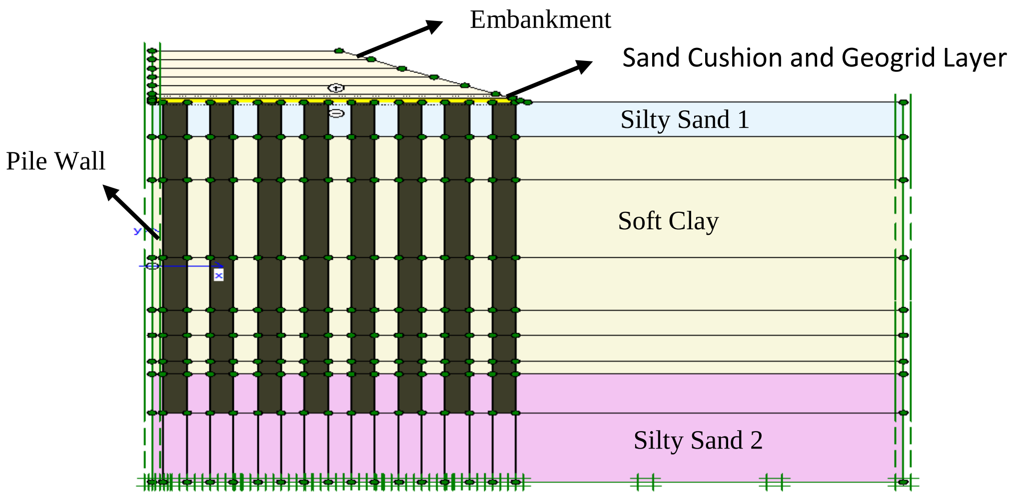

Figure 1: Finite Element Idealization Mesh and Boundary Conditions

The two dimensional plain strain model is implemented to simulate the embankment performance on the existing soil strata using different reinforcement methods. The soil strata and pile wall are simulated using the 15-nodes triangular elements, while the geogrid element layer is approached using the 5-noded geogrid element. The interface between soil/pile and soil/geogrid layer are simulated using linear interface element. The boundary conditions at the bottom of the model, the displacement is restrained in vertical and horizontal directions. While the vertical boundaries, the displacement is restrained in horizontal direction. The construction of the embankment is done in sixth stages, each stage simulate the construction of 1.0 m of embankment.

2.3 *Material Numerical Models*

The embankment fill and the soil strata are modelled using an elastic-plastic model using the Mohr-Coulomb failure criterion, while the pile wall and the geogrid layer are simulated using a linear elastic model. Tables (1) and (2) demonstrate the input parameters of the material models used to simulate behavior of different components of the numerical simulation of the case under study.

Table 1. Numerical Model Materials Parameters for Soil Strata

Stratum	γ_{Bulk} (kN/m^3)	γ_{Sat} (kN/m^3)	k (cm/sec)	E (MPa)	ν	c\ (kN/m^2)	ϕ\ (°)
Silty Sand (1)	18.00	19.50	8×10^{-4}	50.00	0.30	0.10	30
Soft Clay	19.00	20.00	5×10^{-6}	4.50	0.45	25.00	10
Silty Sand (2)	18.00	19.50	8×10^{-4}	100.00	0.30	0.10	35
Sand Cushion	21.00	22.00	2×10^{-3}	25.00	0.30	0.10	30
Embankment Fill	21.00	21.00	2×10^{-4}	30.00	0.30	0.10	32

where γ_{Bulk}: Bulk Unit Weight, γ_{Sat}: Saturated Unit Weight, k: Coefficient of Permeability, E: Effective Elastic Modulus, ν: Poisson Ratio, c\: Effective Cohesion, and ϕ\ : Effective Angle of Internal Friction.

Table 2. Numerical Model Material Parameters for Pile Wall and Geogrid Layer

Material	γ_{Bulk} (kN/m^3)	E (kN/m^2)	ν
Pile	22.0	1000.00	0.20
Geogrid	Tensile Elastic Modulus is 86 MN/m		

2.4 *Out Line of Numerical Analysis Procedures*

Three different cases are utilized in the numerical modelling of the embankment as follows: (i) An unreinforced embankment; (ii) An embankment reinforced with geogrid layer; and (iii) An embankment reinforced with geogrid layer and pile walls. The main purpose of the analyses is to demonstrate the effect of the reinforcement techniques on the following criteria, which affect the embankment performance such as the ground surface settlement, horizontal displacement of the embankment toe and the maximum settlement of the embankment.
The behavior of the geogrid layer and the pile walls reinforced embankment system and their effect in terms of the floating pile walls length variation to demonstrate the beneficial effect of the geogrid and floating pile wall system.

3. ANALYSIS RESULTS

3.1 *Deformation analysis*

Based on the results of the numerical modelling using the finite element method, the settlements of the ground surface beneath the embankment at the end of the construction are demonstrated for the three cases in Figure (2), which shows that the combined system of one layer of geogrid and pile walls are very effective in reducing the total and differential settlement beneath the embankment. While using a geogrid layer is not effective in reducing the total settlement.
Figure (3) shows the maximum settlement at the embankment surface increase in proportion manner with the increase in the height of the embankment. The inclusion of the geogrid layer neither reduce the maximum settlement at any stage of the construction nor the rate of increasing of the maximum settlement with the embankment height. The third case shows that the combination of the geogrid layer and the pile walls has reduced the maximum settlement at any stage of construction b 94 % in average from that in cases (1) and (2).
As shown in Figure (4), the horizontal displacement at the embankment toe is increasing with the raise of the embankment height for the three cases. The use of geogrid layer does not reduce the toe horizontal displacement at any stage of embankment construction. On the other hand the combined system of geogrid layer and pile walls has reduced significantly the toe horizontal movement by 96% in average in compare to cases (1) and (2). The reduction of the toe horizontal displacement significantly improve the stability of the embankment.

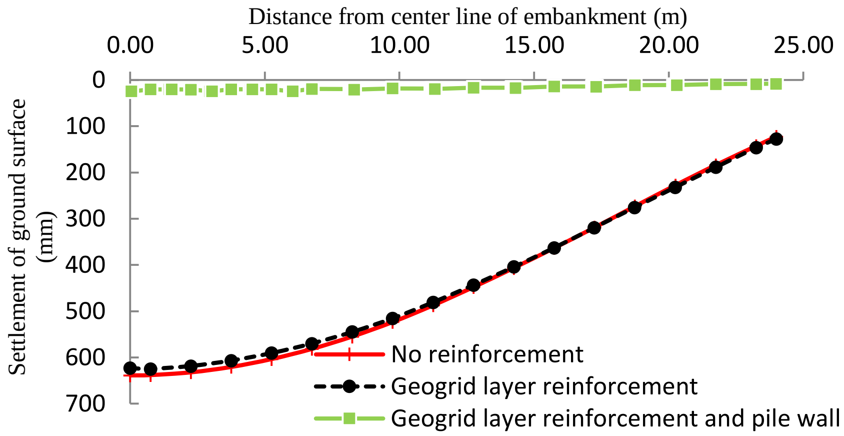

Figure 2: Settlement of Ground Surface under embankment

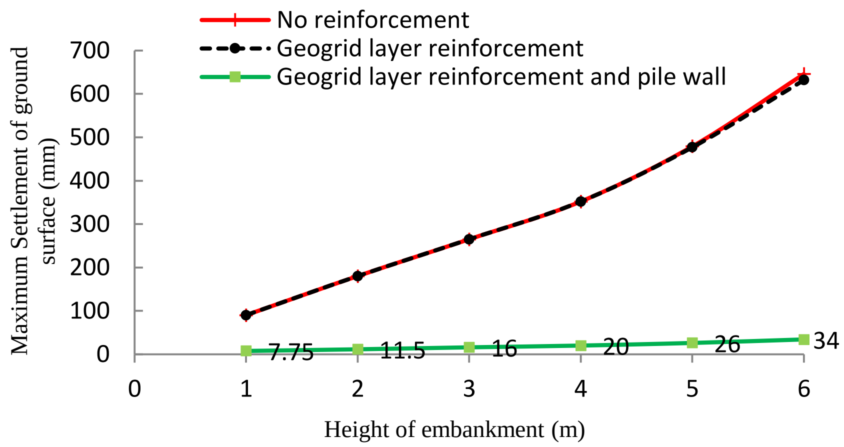

Figure 3: Maximum settlement of ground surface vs. Embankment height

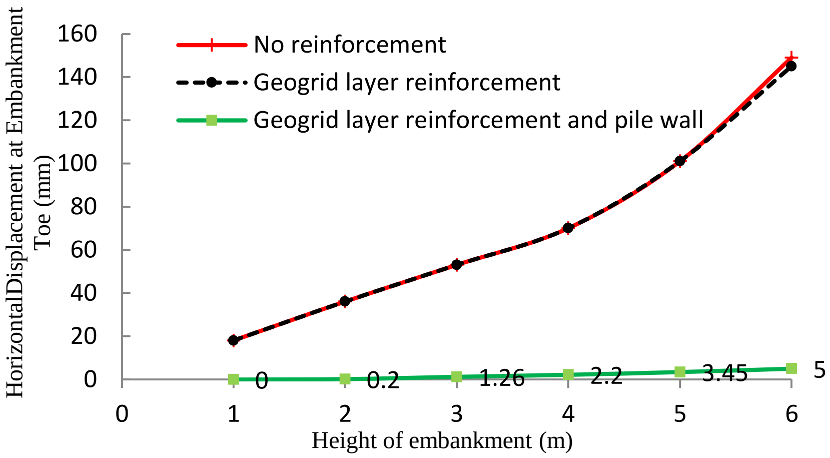

Figure 4: Embankment toe horizontal settlement vs. Embankment height

3.2 *Optimization of the Geogrid and Floating Pile Walls System*

This section is demonstrating the effectiveness of the floating piles in the case of soft clay layer of thickness 27.50 m as the suggested geogrid layer and pile wall system will require eight walls of piles with thickness 1.50 m and length 36.0 m. The total volume of concrete is 432 m^3/m length of the embankment. Two floating pile wall system are titled Cases (4) and (5) as shown in Table 3 and Figure (5), while the ordinary case (i.e. Case (3)) of pile wall is shown in Figure (1).

Table 3. Floating Pile Wall Length.

Case	First Row (m)	Second Row (m)	Third Row (m)	Fourth Row (m)	Fifth Row (m)	Sixth Row (m)	Seventh Row (m)	Eighth Row (m)
3	36	36	36	36	36	36	36	36
4	36	36	30	30	24	24	18	18
5	36	36	27	27	18	18	9	9

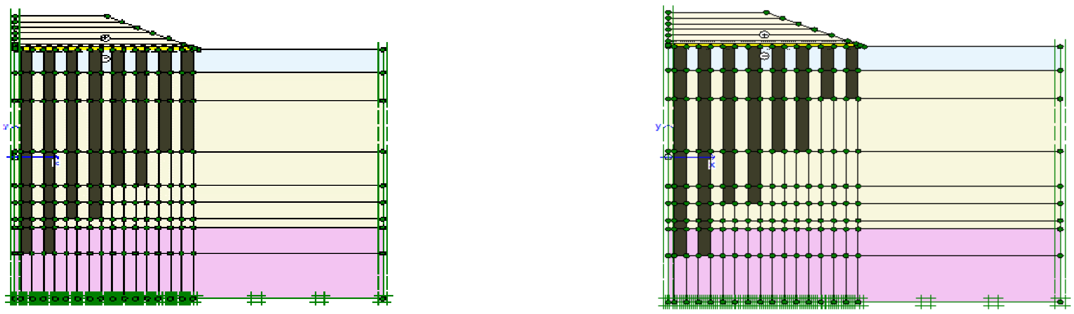

Figure 5: Cases (4) and (5) of Floating Pile Wall and Geogrid layer

Figures (6), (7), and (8) show the results of the displacement analyses for the three cases. In Figure (6), the resulting settlement on the ground surface over distance 5.5 m from center line have increased from 21 mm (Case 3) to 27 mm (Case 4) and 30 mm (Case 5). While the decreasing of the length of the piles from the third row results an increase in the settlement

from 15 mm in average for Case 3 to 53 mm and 75 mm in average for Cases 4 and 5, respectively.Figure (7) demonstrates the increase of settlement with the raise of the embankment height for the three cases. The rate of increasing of settlement is approximately around 5.25 mm, 9.38 mm, and 10.12 mm per one meter height of the embankment. The floating pile walls and the geogrid reinforcement systems has reduced the resulting settlement in the unreinforced embankment by 94%, 84%, and 75% for Cases 3,4, and 5, respectively.
As shown in Figure (8), the horizontal displacement at the embankment toe is increasing with the raise of the embankment height for the three cases. For cases (3) and (4), the horizontal displacement at different stages of construction are the same, while in Case (5), the horizontal settlement increase by 1.75 mm after raising the embankment from height one meter to two meter in compare to 0.2 mm for the other two cases but the max horizontal displacement for the three cases is around 5.0 mm. The combined system of geogrid layer and pile wall has reduced significantly the toe horizontal movement by 96% in average for the three cases. The reduction of the toe horizontal displacement significantly improve the stability of the embankment.

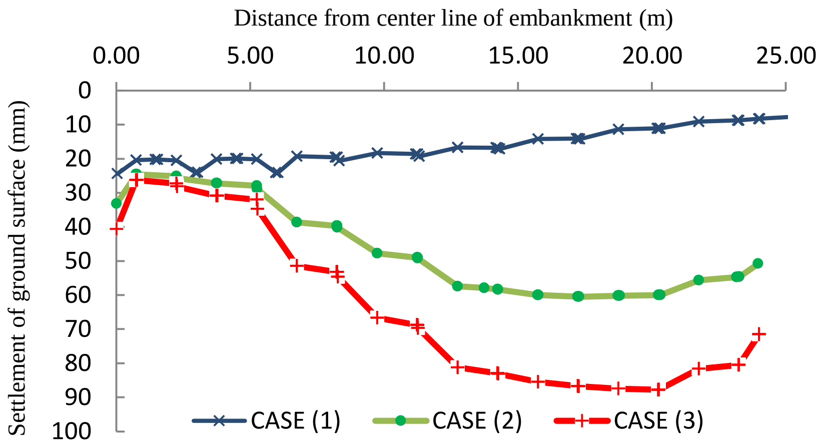

Figure 6: Settlement of Ground Surface under embankment for Cases (1), (2) and (3) of Floating Pile Wall and Geogrid layer System.

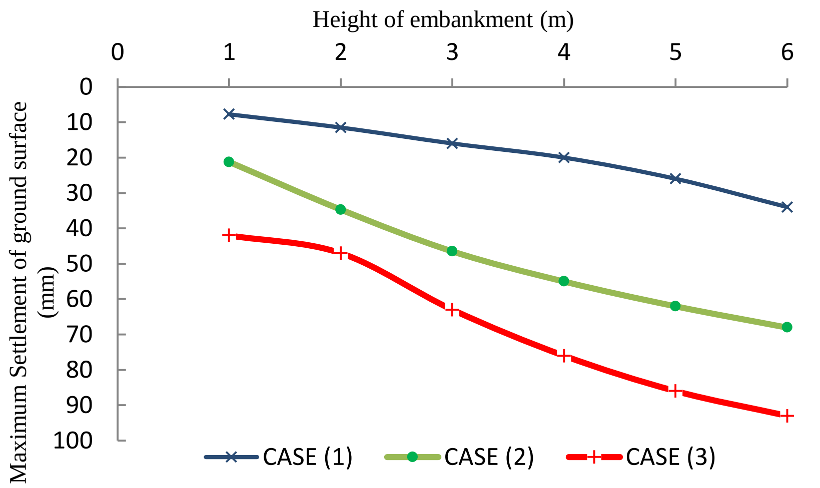

Figure 7: : Maximum settlement of ground surface vs. Embankment height for Cases (1), (2) and (3) of Floating Pile Wall and Geogrid layer System.

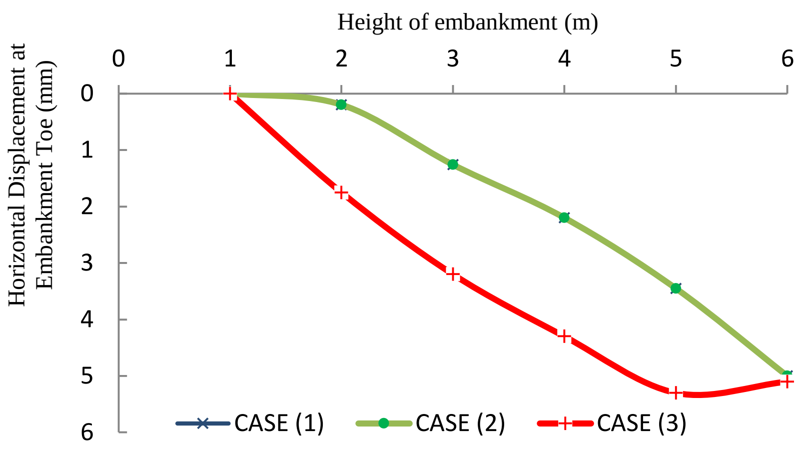

Figure 8: : Embankment toe horizontal settlement vs. Embankment height for Cases (1), (2) and (3) of Floating Pile Wall and Geogrid layer System.

The floating pile wall system in Cases (4) and (5) has effectively reduced the settlement beneath the embankment in the same manner as the ordinary pile wall system and in the same way it reduce effectively the budget of the project by decreasing the concrete volume per one meter length of the embankment along the highway route as shown in Table (4).

Table 4. Floating Pile Walls Concrete Volume.

Case	Concrete Volume (m^3/m)	Reduction %
3	288	---------
4	216	25.00
5	180	37.50

4. CONCLUSION

This paper presents the results of a numerical analysis of the effectiveness of implementing a floating pile walls and geogrid layer syatem to construct an embankment over soft soil ground. The following conclusions are drawn from this study:

1) The existing of four meter surficial dense silty sand layer beneath the embankment has demolished the effect of inclusion of the geogrid layer beneath the embankment in terms of reducing the vertical settlement beneath the embankment and the horizontal settlement of the embankment toe.
2) The combined strengthen system of geogrid and pile wall system are very effective in minimizing the vertical settlement beneath the embankment and at the same time reduce the horizontal settlement of the embankment toe to a negligible value and thus improve and preserve the embankment stability through the construction and post construction stages.
3) In the case of soft clay layer of large thickness, it is effectively to utilize the floating pile walls instead of the ordinary pile walls system by optimizing the pile wall lengths through the cross section of the embankment to minimize the vertical settlement and the embankment toe horizontal displacement as shown in the study.
4) The floating pile walls system has a great impact on the budget of the project as in the case of the high way route.

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