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Effect of Geosynthetic Reinforcement on Pile-Supported Embankment Constructed on Soft Soils

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Abstract—*Geosynthetic reinforced and pile-supported embankment is an effective method to address the problems regarding total and differential settlement, subsoil pressure and, lateral movement of foundation soil during the construction process of highway embankment over soft soils having low shear strength. In this paper, the overall influence of geotextile reinforcement on a pile-supported embankment is evaluated through a numerical analysis to investigate the time-dependent response of the embankment with single layer and multi layers of reinforcement. The effects of the geosynthetic stiffness on total and differential settlements as well as stress reduction ratio are studied. The important observation is that the subsoil settlement decreases with increasing stiffness of single layer geosynthetic reinforcement upto 5000 kN/m and then ceases.*

1. INTRODUCTION

Construction of embankment over soft soils is a very challenging task due to the risk of bearing failure, excessive settlement and lateral movement of foundation soil. Pile-supported embankment is a useful ground improvement method to settle these problems. In this method vertical stiff piles are driven through the soft layers and embedded in a competent substratum beneath to support the granular earth embankment above. The surface and embankment loads are partially transferred to the piles by arching action that occurs in the granular embankment fill material resulting stress reduction on the subsoil. The inclusion of tensile reinforcement enhances the load transfer mechanism and considerably minimizes the maximum as well as differential settlements.

A number of studies have been reported on the arching mechanism and analysis of pile-supported embankment. Terzaghi (1936) described the concept of soil arching through trap-door experiment. Guido et al. (1987) proposed a design criterion which assumes that the load from the fill below the arch is not transferred to piles but carried by the geosynthetic. Hewlett and Randolph (1988) analyzed the arching mechanism in a pile-supported embankment by considering a semi-spherical dome of arching shell.

Low et al. (1994) made some refinements by introducing a factor 'α' for the unreinforced case to incorporate the non-uniform vertical stress on subsoil and then given the formula for SCR, efficiency. Low et al. (1994) developed some equations and charts to assess the stress reduction on the soft ground when the geosynthetic layer is used. Tension in the reinforcement is calculated assuming a circular deflection of the geosynthetic layer across the pile caps. Abusharar et al. (2009) proposed a new method regarding the analysis of piled embankment with some refinements. These refinements are inclusion of a uniform surcharge load over the embankment and the introduction of skin friction mechanism.

Han and Gabr (2002) carried out a numerical study to investigate pile-soil-geosynthetic interaction and concluded that GRPS system reduces settlement and larger stiffness of piles promotes higher soil arching effect.

Liu et al. (2007) conducted a 3D finite element analysis with low area ratio (8.7%) of a case study and compared the results with the field data. Liu et al. (2009) proposed a new method of using large diameter, cast-in-situ concrete pipe piles to support the embankments for bridge approaches. Jenck et al. (2009) performed a numerical analysis of a piled embankment and the three dimensional aspect of the problem is highlighted in their paper.

Briancon and Simon (2012) investigated the performance of piled embankment over soft soil through a full-scale experimental study and reported how load transfer mechanism is different for single and multilayer reinforcement. Bhasi and Rajagopal (2014) conducted a 3D finite element analysis to predict the performance of geosynthetic reinforced piled embankment with single and multilayer of reinforcement. Rowe and Liu (2015) performed a fully coupled and fully three dimensional finite element analyses for an embankment to study the behavior of the same under different ground improvement techniques.

In this paper an embankment is modeled in PLAXIS 2D and the effect of geotextile reinforcement on the performance of pile-supported embankment is evaluated.

2. FINITE ELEMENT MODELLING

Numerical model is a mathematical simulation of a real physical process. The numerical analysis is performed using the finite-element software PLAXIS 2D. Fig. 1 shows the finite-element mesh used in the analysis. The 23m wide embankment is 5m high having a side slope of1Vto 1.5H. The layered soft foundation is 9.5m deep. The water table is 2m below the ground surface. The subsoil profile is modeled with a rough rigid bottom boundary.

To minimize boundary effects, the lateral boundary of the finite-element mesh is extended 23m horizontally either side of the embankment. The line of symmetry and far field lateral boundaries (the planes of x= 0m and x = 69m) are smooth rigid i.e. Zero displacement in the x-direction. First only rigid piles are used under the base of the embankment to improve the soft ground and its impact is evaluated. Then one layer of geotextile of stiffness 800 kN/m is placed over the piles within two gravel layers of total thickness of 0.55m. The performance of each improvement method is compared with the unimproved section of the embankment. The 0.38m diameter and 8.3m long piles are placed at a spacing of 2m centre to centre.

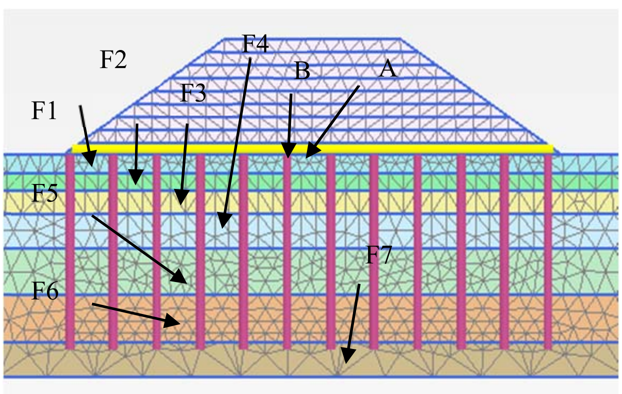

Fig. 1: Finite element mesh model of the embankment

A linear elastic-perfectly plastic model with Mohr-Coulomb failure criterion is utilized for simulating the embankment fill and gravel layer. Because of the stress dependent stiffness, the foundation soil profile is modeled with soft soil model available in PLAXIS 2D. Here the 15-node triangular soil element is used. The stiff pile is modeled with 5-node embedded pile element which is isotropic linear elastic material. The elastic modulus of pile is 20 GPa. Isotropic geogrid element is used for geotextile. The stiffness of geotextile is 800 kN/m. Table1 presents the properties of the various subsoil layers. In this table, λ is slope of virgin consolidation line, κ is slope of swelling line, C_c is compression index, Cr is recompression index, Φ' is effective friction angle, c' is effective cohesion, Kv is vertical hydraulic conductivity, and Ko is coefficient of earth pressure at rest. The properties of embankment fill, gravel and pile are given in Table 2.

3. METHODOLOGY

The seven layered foundation soil is constructed in one step in the first phase. Then piles are installed using the embedded pile option in the very next phase. After that The embankment construction is modeled in 9 steps with 17 days of consolidation analysis for the unimproved section and 31 days for the other two improved sections. The whole system is kept for 149 days of monitoring period after the end of embankment construction i.e. a total of 180 days from the start of embankment construction.

4. RESULTS AND DISCUSSION

For each ground improvement case and the unimproved case some nodal points are marked on the embankment model to find the desired settlement. Point ‘A’ (34.5m, 0m) is chosen on the top of subsoil at the mid-section for the measurement of settlement.

4.1. Influence of Reinforcement Layers on Settlement and Load Transfer

When geotextile layer is used as reinforcement, it is kept a certain distance above the pile head to avoid the risk of damage through rubbing action. Depending upon the height of the embankment and spacing between the piles multilayer of reinforcement can be used. In this finite element analysis the number of geotextile layers is varied from one to three keeping the vertical distance between them constant at 250 mm. In the first trial, the tensile modulus of the geotextile is kept same i.e. 800 kN/m for all the layers starting from one to three. The effect of increasing the number of geotextile layers on the settlement of subsoil surface and the maximum tensile force developed in each layer of the reinforcement is studied. At the end of the construction period and as well as the monitoring period the subsurface settlement gets minimized with increase the number of reinforcement layers as shown in Fig. 2. The settlement of the embankment surface reduces with the increasing layers of geotextile having high tensile modulus.

Table 1: Properties of the soft foundation soils (Rowe and Liu, 2015)

Layer	F1	F2	F3	F4	F5	F6	F7
Thickness (m)	0.75	0.75	1	1.5	2	2	1.5
λ	0.092	0.191	0.308	0.074	0.116	0.088	0.027
κ	0.014	0.029	0.046	0.011	0.017	0.013	0.004
C_c	0.212	0.44	0.71	0.171	0.267	0.203	0.062
C_r	0.032	0.066	0.107	0.026	0.040	0.031	0.009

Φ' (deg)	30.6	30.6	30.6	30.6	27	27	34
c' (kPa)	4	4	4	4	13	13	0
K_v (m/day)	$6.91*10^{-5}$	$6.91*10^{-5}$	$1.2*10^{-8}$	$1.4*10^{-7}$	$8.3*10^{-8}$	$8.3*10^{-8}$	$8.9*10^{-6}$
K_o	1.668	0.986	0.686	0.574	0.662	0.619	0.52

Table 2: Properties of gravel, fill and, pile (Rowe and Liu, 2015)

Material	Unit weight (kN/m^3)	Friction angle (degrees)	Cohesion (kPa)	Young's modulus (MPa)	Poisson's ratio
Fill	18.5	30	10	20	0.3
Gravel	20	36	60	70	0.3
Pile	24	-	-	20000	0.2

Table 3: Maximum tensile forces developed in the reinforcement layers

Stiffness of Reinforcement (kN/m)	No of Layers Used	Layer	Max. Tensile Force (kN/m) after construction of embankment	Max. Tensile Force (kN/m) at the end of consolidation process
800	1	Bottom layer	9.92	11.99
800	2	Bottom layer	7.419	10.36
		Upper layer	5.890	8.21
800	3	Bottom layer	8.33	10.56
		Middle layer	4.64	6.29
		Upper layer	3.28	5.51
400	2	Bottom layer	5.36	6.68
		Upper layer	3.45	5.09
267	3	Bottom layer	4.19	5.54
		Middle layer	2.15	3.04
		Upper layer	1.90	3.01

As a result the differential settlement also reduces with increasing height of embankment. This can be well confirmed from the lesser reinforcement forces developed in the upper and middle layers of geotextile (Table 3) than the bottommost layer. It is also found that the tensile force developed in the reinforcement layer is larger around the periphery of the piles because of the high differential settlement.

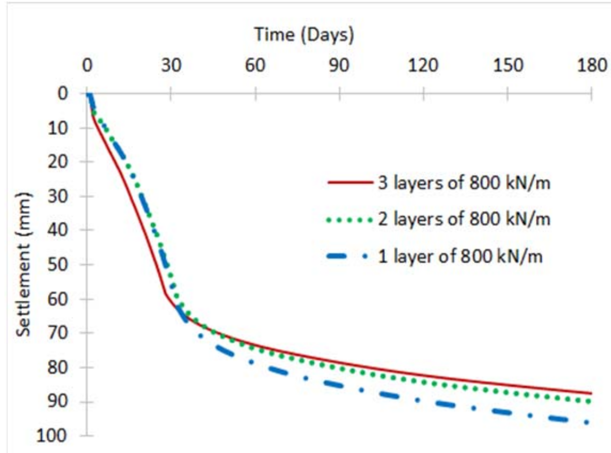

Fig. 2: Effect on settlement of multilayer reinforcement having same modulus

In the second set of analyses, the total tensile modulus of the geotextile 800 kN/m is equally divided among the layers when it is used as two-layer system and three-layer system. In two-layer system, each of the reinforcement layer has modulus of 400 kN/m and in three-layer system, each layer is strengthened by 267 kN/m tensile modulus geotextile. Fig. 3 shows the settlement of foundation soil surface.

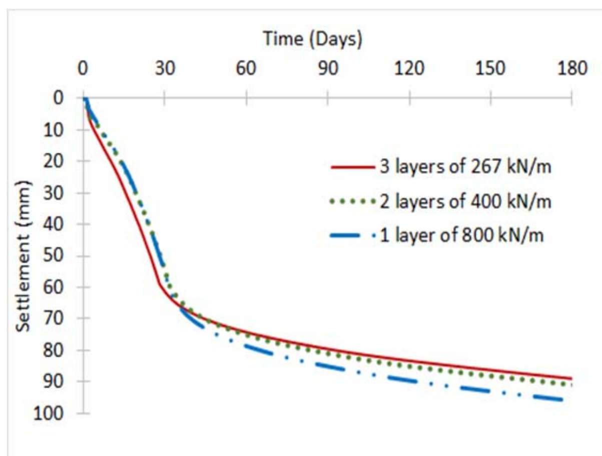

Fig. 3: Effect on settlement of multilayer reinforcement having different modulus

The tensile forces developed in each layers of reinforcement for different combination are shown in Table 3. It is well observed that the tensile force developed in the bottom layer for a single layer case is higher than the forces developed in the same layer for the two and three layer systems where the total stiffness of the reinforcement is equally divided among the layers. This happens due to the lower value of modulus of the reinforcement. At the end of construction, the total force developed in one, two and three layer system are 9.92 kN/m, 8.81 kN/m and, 8.24 kN/m respectively. But at the end of consolidation period these values are higher. They are 11.99

kN/m, 11.78 kN/m and, 11.59 kN/m respectively. This increase in the forces is due to the differential settlement which occurred during the consolidation process of the soft foundation soil.

4.2. Effect of Geotextile Tensile Modulus on Settlement and Differential Settlement

The effect of geotextile tensile modulus on maximum and differential settlement is studied by varying the tensile modulus from 800 kN/m to 10000 kN/m. These settlements are measured at the end of the consolidation period. Fig. 4 shows how the maximum settlement of the foundation soil varies with different modulus values. Maximum settlement decreases with increase of modulus value upto 5000 kN/m and then becomes constant with further increase in modulus value. The effect on differential settlement is shown in Fig. 5. The differential settlement is measured between the pile head (Point B) and the middle point of the sub-soil between two piles (Point A). Here also the differential settlement decreases with increasing stiffness of geotextile upto 5000 kN/m. Further increase in stiffness value does not affect the differential settlement.

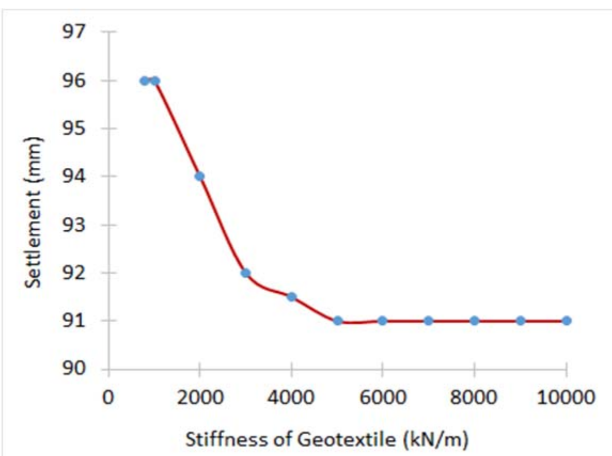

Fig. 4: Effect of geotextile stiffness on settlement

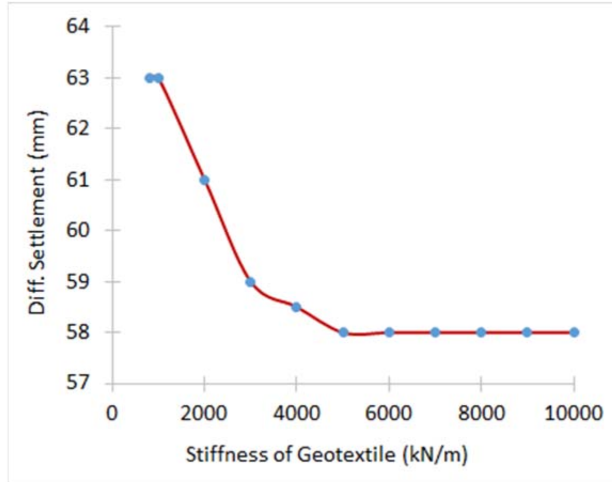

Fig. 5: Effect of geotextile stiffness on differential settlement

4.3. Effect of Geotextile Tensile Modulus on Stress Reduction Ratio

Stress reduction ratio (SRR) is defined as the ratio of the stress applied on the top of sub-soil to the total stress coming from the embankment. This SRR=0 represents complete soil arching and SRR=1 represents no soil arching. Fig. 6 shows the development of arching phenomenon through the principal stress orientation. From the numerical result it is clearly seen that the soil arching in the embankment fill material forms an arching shell with a shape of hemispherical dome which was assumed by Hewlett and Randolph (1988).

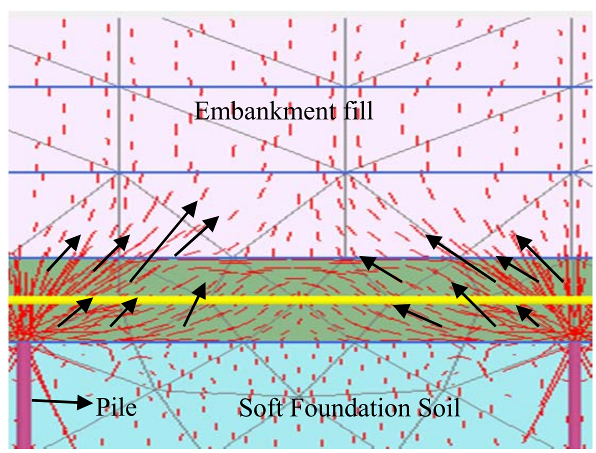

Fig. 6: Development of soil arching

Fig. 7 shows the effect of geotextile stiffness on the stress reduction ratio. With the increase of stiffness value SRR is increasing too but after 6000 kN/m it stabilizes. In the theoretical solutions of Hewlett and Randolph (1988) and British Standard BS8006 (1995) the effect of geotextile was not considered. But numerical result shows that it plays an important role in soil arching phenomenon and consequent stress reduction on sub-soil.

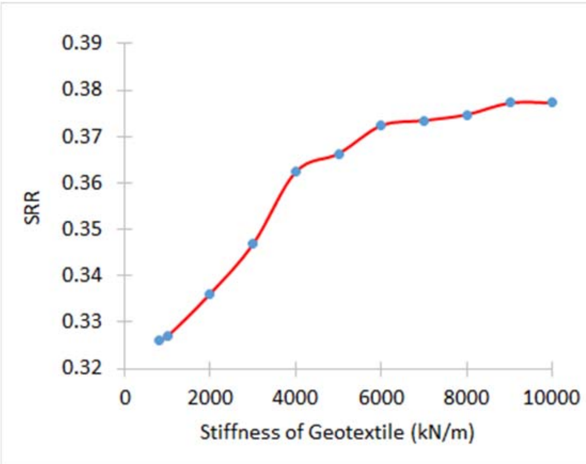

Fig. 7: Effect of geotextile stiffness on stress reduction ratio

As the geotextile gets stiffer, differential settlement gets minimized resulting in reduction of soil arching action. So load transfer onto the piles gets minimized and stress on foundation soil increases accordingly. Fig. 8 indicates how vertical stress on foundation soil gets reduced with the incorporation of geotextile layer. It shows that at the end of consolidation the vertical stress coming on the soft soil surface is reduced by 62% with the use of one layer of geotextile having a stiffness of 800 kN/m along with piles compared to the case where no piles and geotextile layer are used to support the embankment.

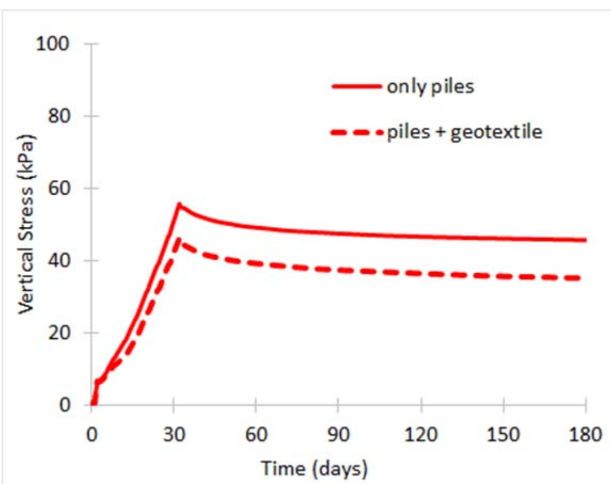

Fig. 8: Vertical stress on foundation soil

5. CONCLUSIONS

Based on the finite element numerical analysis carried out to assess the performance of a geotextile reinforced pile-supported embankment, the following are the conclusions:

1. This geotextile reinforced pile support system minimizes the total and differential settlement of foundation soil as well as vertical stress on the sub-soil.
2. There is 50.8% reduction in vertical stress on foundation soil when only piles are used for support but with the use of one layer of geotextile of stiffness 800 kN/m along with the piles, this reduction increases to 62%.
3. The total settlement of foundation soil at the centre of the embankment is reduced by 50% and 65.3% when piles are used for support with and without geotextile layer respectively. The subsoil settlement is found to be almost same at the centre of the embankment for both the cases of single geotextile layer with high stiffness and three layer system with same total stiffness as previous. This indicates that not the number of layers but the total stiffness of the geotextile reinforcement is dominant as far as the reinforcing action is concerned.
4. The tensile force developed in the bottom layer for a single layer case is higher than the forces developed in the same layer for the two and three layer systems where the total stiffness of the reinforcement is equally divided among the layers. But the total tensile force developed in all the layers of the geotextile reinforcement is almost same irrespective of the number of layers used at the embankment. The increase in the tensile force after consolidation process is due to the differential settlement of the foundation soil during that period.
5. The maximum and differential settlements decrease with increase of geotextile stiffness value upto 5000 kN/m but further increase in stiffness value does not effect the total as well as differential settlement.
6. The stress reduction ratio also gets increased with the increase of geotextile stiffness but when the stiffness value crosses 6000 kN/m, the stress concentration ratio becomes almost constant.

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