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Numerical Simulation of Compaction in a Pile-Supported Embankment

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ABSTRACT
Geosynthetic-reinforced pile-supported embankments are widely used as a geotechnical solution for constructions over soils with high compressibility and low bearing capacity, such as soft soils. In this type of structure, soil arching and the membrane effect control stabilization. These effects are responsible for transferring most of the embankment loads and surcharges to the piles. Using the finite element code Plaxis 2D 2016, parametric analyses were performed aiming to evaluate the effect of induced stress due to soil compaction (CIS), geosynthetic stiffness, embankment height and spacing between caps on the behavior of these structures. In the numerical analyses, the pile-supported embankment was modelled with a trapdoor under plane strain condition, which was proposed by Terzaghi (1936). In this work, the effect of the factors mentioned previously on the differential settlement at the top of the embankment, the geosynthetic deflection and the mobilization of tensile load along the reinforcement were analyzed. Results show that the reinforcement stiffness, height of the embankment and spacing between caps are the most important factors in the structural behavior. Moreover, for structures with lower ratio between the height of the embankments and spacing between caps, the CIS may reduce the differential settlement at top of the embankment.

1. INTRODUCTION

Pile embankments with geosynthetic reinforcement are widely used for construction over soft soils. Their main advantages are the short time of construction due to the soft soil consolidation having a minimum influence on the pile embankment, negligible residual settlements, and low effect on sensitive adjacent structures (Van Eekelen et al., 2015). In this type of structure, most of the embankment loads and surcharges are transferred to the piles by two different phenomena, which are the arching effect and the membrane effect. The arching effect is the transference of pressure between a yielding soil mass and a stationary soil through a shear stress that is developed in the interface between these two masses in order to counteract the settlement of the yielding mass (Terzaghi, 1943). The membrane effect refers to the ability of the geosynthetic to deform and absorb the mobilized normal stress in the geosynthetic surface through tension (Gourc and Villard 2018). As the soft soil settles, the soil above yields and the geosynthetic is responsible for bearing the load of the soil mass weight not transferred to the piles directly by the arching effect. Thus, this load is transferred to the pile caps indirectly by the membrane effect.

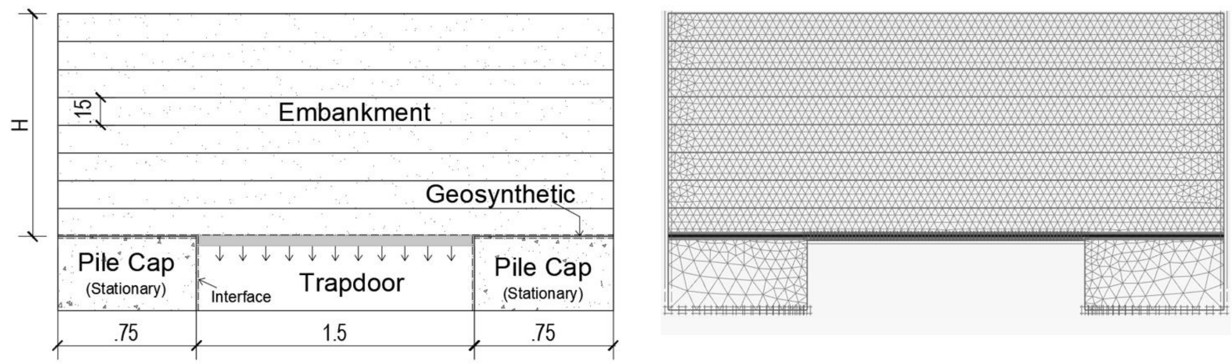
The arching effect was first investigated by Terzaghi (1936). The experiment consisted of a layer of dry sand placed on a platform that contains a trapdoor. As the trapdoor is lowered, the reduction of the pressure over the trapdoor is monitored and the arching effect is identified. This experiment is typically called the trapdoor experiment and many researchers have made similar physical models, including Hewlett and Randolph (1988), Low et al. (1994), Horgan and Sarsby (2002), Jenck (2007), Chen et al. 2008, Zhu (2012), Van Eekelen (2013), Rui et al. (2016), Al-Naddaf (2017), Dieguez (2019).

The transference of embankment loads and surcharges due to the arching effect is more active when the soil parameters are increased or the pile embankment configuration is enhanced (Van Eekelen, 2012a). Aside from the effect of CIS, backfill compaction leads to increased soil resistance and stiffness. In general, compaction lead to better results when it is applied in relatively thin layer of backfill, typically between 0.15 and 0.30 m thick (Ehrlich and Mitchel, 1994). When the compaction equipment is over a backfill layer, there is an increase of the vertical and horizontal stress. After this occurs, the vertical stress returns to its original value before the compaction, in contrast to the horizontal stress, which remains higher. This increase in the horizontal stress is a result of the non-elastic behavior of the soil. The CIS leads to an increased horizontal residual stress in the embankment, which is greater than the geostatic stresses provided by the embankment's final height (Mirmoradi and Ehrlich, 2018).

The analytical methods of design for geosynthetic pile-supported embankments, such as the methods suggested in BS8006 (2010) and CUR226 (2016), do not take into consideration the effects of induced stress due to soil compaction (CIS). In the present study, using the finite element code Plaxis 2D 2016, parametric analyses were performed aiming to evaluate the effect of CIS, geosynthetic stiffness, embankment height and spacing between caps on the behavior of these structures. In the numerical analyses, the pile-supported embankment was modelled with a trapdoor under plane strain condition, proposed by Terzaghi (1936). The effects of the factors mentioned previously on the differential settlement at the top of the embankment, the geosynthetic deflection and the mobilization of tensile load along the reinforcement were analyzed.

2. NUMERICAL MODELLING

The numerical modelling was made using the finite element software Plaxis 2D 2016. The simulation consists of a trapdoor experiment theorized by Terzaghi (1936), with the addition of a geosynthetic layer. The longitudinal section of the embankment designed in the numerical model is presented in Figure 1.a. The model simulates a plane strain condition, considering a mesh of six-node-triangular elements (Figure 1.b). Typical values of pile-supported embankments were considered for geometry and material parameters. Parameters for the embankment soil, the concrete of the pile caps, the steel plane of the trapdoor and interfaces are presented in Table 1. The embankment soil is a granular sand and was modelled with the hardening soil model. Linear elastic behavior was assumed for the other materials



a) Schematic model b) Mesh considered in the numerical model

Figure 1. Longitudinal section of the embankment designed in the numerical model.

The model length is 3.0 m, where the trapdoor is 1.5 m and each stationary support is 0.75 m. The stationary support represents half of a 1.5 m concrete-pile cap. The parametric analyses considered four different heights for the embankment (H): 1.2 m, 1.5 m, 1.8 m and 2.1 m. The arching effect and critical height of the embankment (the lower plane where no differential settlement occurs (Naughton 2007)) were evaluated.

The geosynthetic was placed above the trapdoor and stationary supports. Two different values of reinforcement stiffness were considered in the analysis: 2500 kN/m and 5000 kN/m. The trapdoor was kept stationary during embankment construction and only released to settle after the last construction steps were simulated; soil layers placement and compaction. Displacement increments of 1 mm were iterated until reaching 100 mm. Following, displacement increments were increased to 100 mm and iterations continued until contact between the geosynthetic and trapdoor had ceased. At this point, the maximum deflection of the embankment was obtained. The trapdoor settlement was simulated by applying a line displacement under the platform.

In the performed numerical modelling, the lateral boundaries were free to move in the vertical direction but blocked in the horizontal direction. The lateral border of the model represents the middle of the pile caps. In the prototype, due to its symmetrical condition, these planes have no lateral displacements. Movement of the inferior boundary was blocked in both directions.

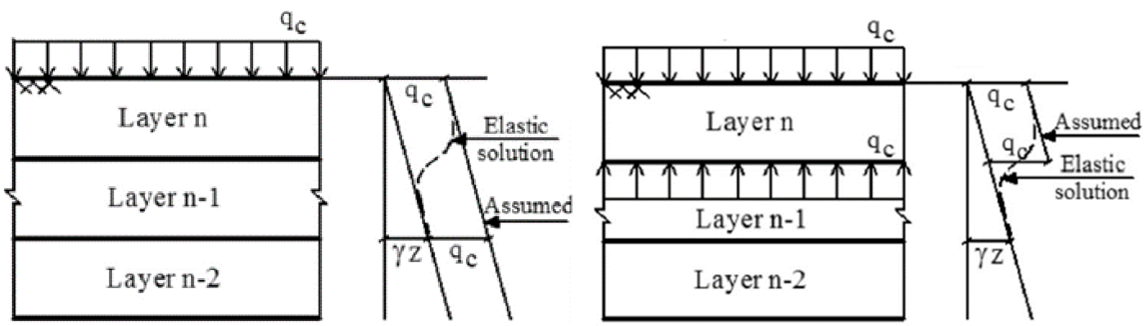
2.1 Numerical Compaction Modelling

Modelling of the backfill compaction followed the procedure suggested by Mirmoradi and Ehrlich (2015), in which compaction is simulated by applying an equal distribution load at the top and bottom of each soil layer in a single step. These authors state that when applying the distribution load only above the soil layer (Figure 2.a), the induced stress leads to a constant increase of the vertical stress in all layers already placed. In contrast, applying the load on the top and bottom of the soil layer (Figure 2.b) leads to an increase in vertical stress only in the layer considered.

In Figure 2, the dashed line curve represents the elastic solution of the vertical stress increment with depth during compaction. This curve shows that the maximum increment in vertical stress occurs during contact with the compaction equipment and reduces with depth. Ehrlich and Mitchel (1994) recommend that the compaction layers should be between 0.15 and 0.30 m thick and all points within the layer undergo the same maximum increment in vertical stress. Following these recommendations, it was assumed during the construction step that the soil vertical stress induced due compaction was 120 kPa and each backfill layer was 0.15 m thick.

Table 1. Material Properties.

Property	Value
Soil properties	
Model	HS
Unit weight, γ (kN/m3)	20
E_{50}^{ref}, (kPa)	50,000
E_{ur}^{ref}, (kPa)	150,000
Stress dependence exponent, m	0.5
Peak plane strain friction angle, ϕ (°)	40
Cohesion, c (kPa)	1
Dilation angle, Ψ (°)	10
Poisson's ratio, ν	0.25
Failure ratio, Rf	0.8
Reinforcement J2500	
Elastic axial stiffness (kN/m)	2,500
Reinforcement J5000	
Elastic axial stiffness (kN/m)	5,000
Concrete-geosynthetic interface	
Friction angle (°)	37
Cohesion (kPa)	0.1
E (kPa)	45,000
Geosynthetic-soil interface	
R_{inter}	0.9
Geosynthetic-trapdoor interface	
Friction angle (°)	30
Cohesion (kPa)	0
E (kPa)	100
Concrete-trapdoor interface	
Friction angle (°)	1e-3
Cohesion (kPa)	0
E (kPa)	100



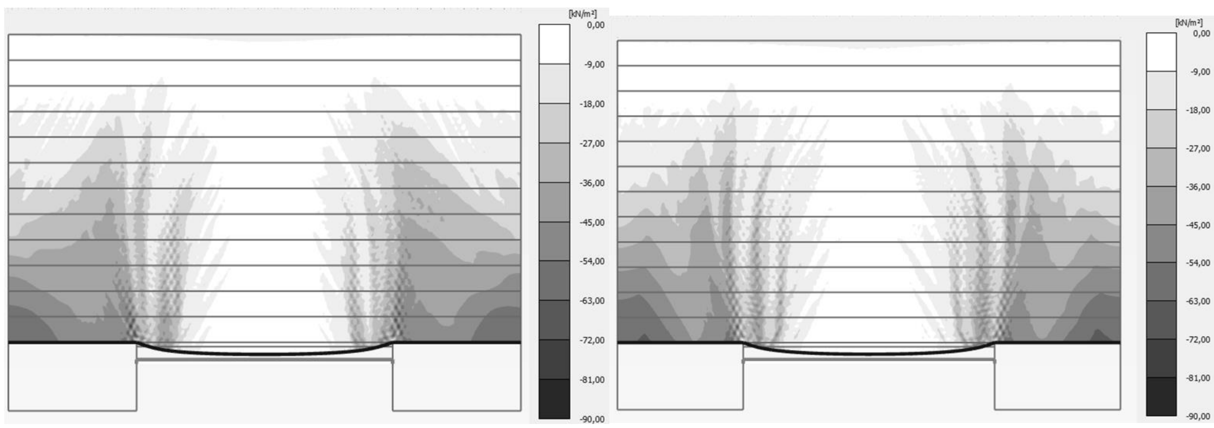
a) Distributed load at the top of the soil layer

b) Distributed load at the top and bottom of the soil layer

Figure 2. Modeling of the vertical stress load during compaction of the backfill soil layer “n” (Adapted from Mirmoradi and Ehrlich 2015)

3. RESULTS AND DISCUSSION

Figure 3 presents the vertical stress through the embankment following trapdoor release. Figure 3.a and 3.b show results of analyses not considering and considering CIS in the model, respectively. In both analyses, embankments are 1.8 m high and the stiffness of the geosynthetic is equal to 5,000 kN/m. Before platform release, vertical stress through the embankments were similar in both tests, equal to the overburden stress of soil. However, after platform release, the vertical stress over the stationary supports (pile caps) increased and vertical stress over the yielding soil mass decreased. These findings indicate that the “arching” effect occurred in both scenarios (with and without CIS included in the model). Similar results were obtained in the other performed analyses.



a) Without CIS modelling   b) With CIS modelling

Figure 3. Vertical stress after trapdoor settlement for embankments 1.8 m high.

Figure 4 shows the tension mobilization along the geosynthetic reinforcement for analysis, assuming CIS in the model, embankments 1.8 m high, and axial stiffness of 5,000 kN/m. The maximum tensile load was observed in the middle of the geosynthetic and the minimum tensile load was observed in the lateral boundary of the model, which represents the middle of the pile cap (symmetry plane). Table 2 presents the mobilized tensile load determined at the 4 points shown in Figure 4, for each of the sixteen models performed. Point A is located 0.10 m after the lateral boundary of the model, Points B and C are 0.10 m before and after the edge of the stationary support, respectively, and point D is in the middle of the trapdoor. As shown in Table 2, all models are similar to the one presented in Figure 4. It was observed that the tension close to the stationary boundary is close to zero in most of the models, except for those with a normalized height of 0.8 and geosynthetic stiffness equal to 5,000 kN/m. Table 2 also indicates that the ratio of the tension loads at Point C (the point located 0.10 m from edge of the trapdoor) and Point D (the location of maximum tension) is approximately 90%.

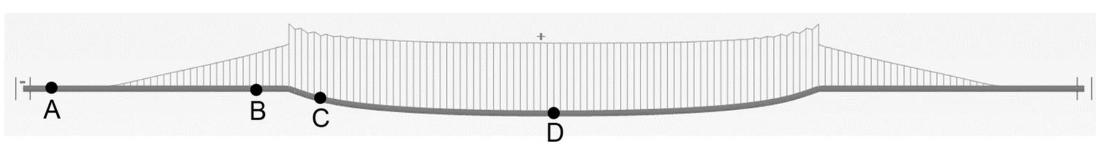


Figure 4. Tensile stress distribution in the geosynthetic after trapdoor settlement for embankments 1.8 m high.

Table 2. Tensile loads in the reinforcement at locations A, B, C and D (Figure 4) for each of the sixteen models.

Reinforcement stiffness (KN/m)	CIS modelling	h/(s-a)	Tensile loads (KN/m)			
			A	B	C	D
5000	without	0.8	3.25	20.0	34.2	38.4
		1.0	0.62	20.1	35.8	40.0
		1.2	0.43	20.2	36.4	40.5
		1.4	0.33	20.4	37.2	40.2
	with	0.8	1.87	19.4	33.6	37.7
		1.0	0.46	19.7	35.6	39.3
		1.2	0.26	19.8	35.2	39.3
		1.4	0.22	19.9	35.4	39.2
2500	without	0.8	0.07	13.5	28.9	32.2
		1.0	0.04	13.3	30.1	33.3
		1.2	0.06	13.1	30.5	33.5
		1.4	0.09	13.4	31.1	33.4
	with	0.8	0.04	12.8	28.3	31.4
		1.0	0.04	12.9	29.7	32.6
		1.2	0.05	13.0	30.3	32.8
		1.4	0.05	12.7	30.3	32.5

Figure 5 shows the effect of the maximum tensile load mobilized on the reinforcement (Point D, Figure 4) of the CIS in the model, the reinforcement stiffness and the normalized height of the embankment (H/(s-a)), where (s-a) is the length of the trapdoor. Considering or omitting the CIS in the model, the tensile load on the geosynthetic assuming a reinforcement stiffness of 5,000 kN/m is about 20% higher compared to a reinforcement stiffness of 2500 kN/m. For normalized heights lower than 1.0, the height of the embankment has a significant influence on the mobilized tensile load applied to the reinforcement. For values greater than 1.0, the tensile load on the reinforcement is almost the same. Moreover, the variation in tension load on the reinforcement due to the CIS included in the model is lower than 3%.

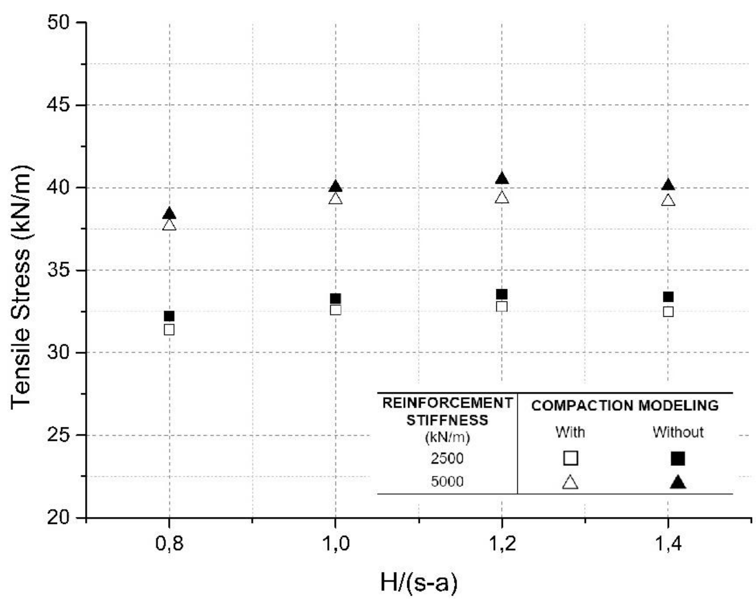


Figure 5. Tensile load on the reinforcement versus normalized embankment height for different stiffness of reinforcement, considering or omitting the CIS in the model.

Figure 6 shows results of the normalized geosynthetic deflection, d/(s-a), versus the normalized height of the embankment and the stiffness of the reinforcement at the end of the trapdoor release, considering or omitting the CIS in the model. Increasing the stiffness of the reinforcement led to a significant decrease in geosynthetic deflection. Because of the improvement of soil “arching”, the increase of embankment height also led to a decreased deflection for the reinforcement. Including CIS led to a decreased deflection for the geosynthetic, but the effect was negligible.

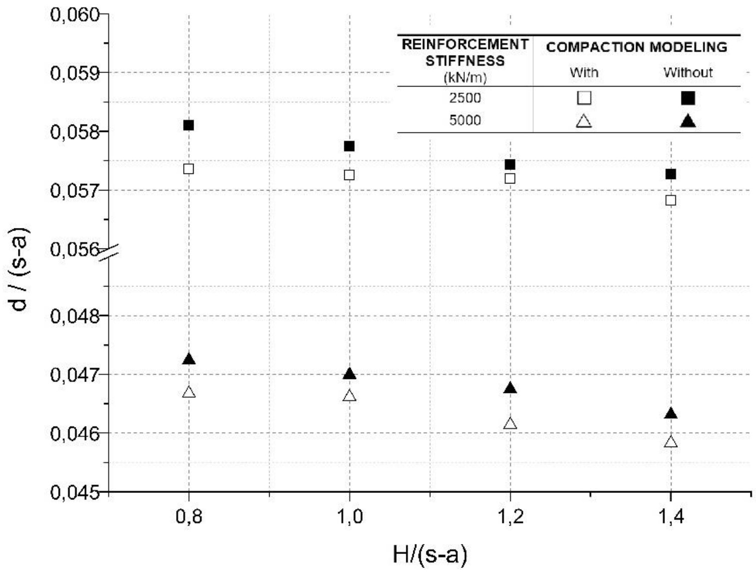


Figure 6. Normalized deflection versus normalized embankment height for different stiffness of reinforcement, considering or omitting CIS in the model.

Figure 7 presents results of the normalized differential settlement at the top of the embankment, δ/(s-a), versus the normalized height of the embankment and the stiffness of the reinforcement at the end of the trapdoor release, considering or omitting CIS in the model. An increase in the geosynthetic stiffness and the height of the embankment reduces the differential settlement at the top of the embankment. Analyses indicated that, for lower height embankments, CIS included in the modelling led to a reduction in the differential settlement. Nevertheless, as the embankment height increases this effect becomes negligible.

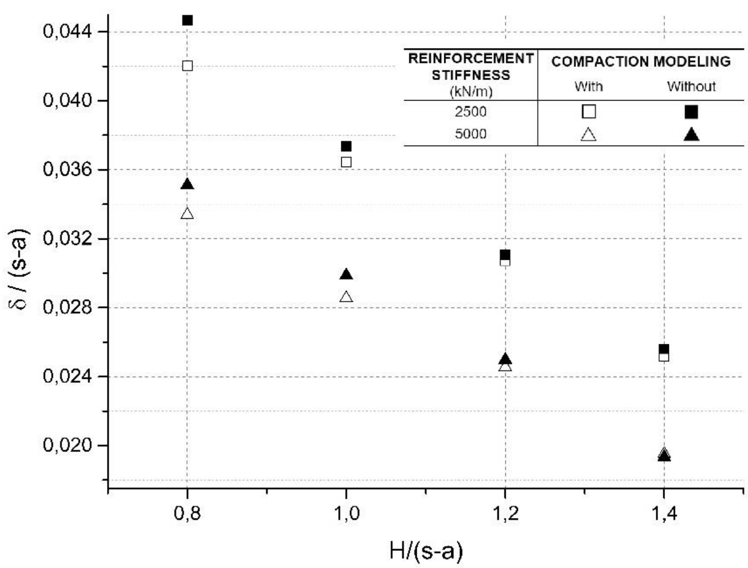


Figure 7. Normalized differential settlement versus normalized embankment height for varying stiffness of reinforcement, considering or omitting CIS in the model.

4. CONCLUSIONS

In this paper, numerical simulations of trapdoor experiments were performed in order to analyze the influence of soil compaction in pile-supported geosynthetic reinforced embankments. Sixteen simulations were modelled, in which compaction condition, geosynthetic stiffness and embankment height were varied. The effects of these factors on the mobilized tensile load along the reinforcement, geosynthetic deflection and differential settlement at the top of the embankment were assessed.

In the performed analyses, the formation of soil "arching" was observed, in agreement with Terzaghi (1943). Results show the vertical stress over pile caps increase and the vertical stress over the yielding soil mass decrease during the trapdoor release. Increasing geosynthetic stiffness and embankment height led to significant decreases in the deflection of the geosynthetic and the differential settlement at the top of the embankment. Following trapdoor release, different distributions of vertical stresses in the embankment were observed when CIS was included in the modelling. The CIS effect on the differential settlement at the top of the embankment was significant when the embankment height normalized by the trapdoor length was lower than 1.0. Therefore, these analyses indicated that the influence of CIS may be neglected if the normalized height of the embankment is greater than 1.0. Moreover, CIS included in the modelling had a small influence on tensile load and deflection of the geosynthetic.

Note that in the performed study, the backfill layers had been placed and compacted, and no horizontal strain of the soil and reinforcement occurred before the trapdoor was released to settle. Nevertheless, under real field conditions, the effect of CIS may be higher because the settlement of the soft soil and lateral displacement of the embankment may occur during construction. In this scenario, backfill compaction leads to increased soil resistance and stiffness.

5. ACKNOWLEDGEMENTS

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