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Comparison of behaviour of basal reinforced piled embankment with two layer of reinforcement

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Abstract. Interest to basal reinforced piled embankments is increasing recently due to their rapid construction and reliability. A comprehensive parametric study is conducted to determine effects of pile properties, reinforcement stiffness, embankment properties and soft soil properties into settlements, pressures and excess pore water pressure development and dissipations. Results which are obtained by using one-layer reinforcement during construction are compared with the results obtained by using two-layer reinforcement during construction. Finite element method is used during the parametric study. Second layer of reinforcement is placed ın five different positions in order to reveal effects of reinforcement position into behaviour. Traffic load is also taken into consideration during the study. Differences between the results without presence of traffic loading and with presence of traffic loading is stated in this the study.

Keywords: consolidation; settlement; geosynthetics; pile; embankment

1. Introduction

Existing roads are widened or new roads are constructed due to increasing demands. This situation brings up excessive consolidation problem, because especially construction area of new roads passes over soft soils. Excessive settlements should be avoided to provide safe driving for drivers and also to reduce maintenance costs. Several methods can be used to solve consolidation problem. Hegde and Shitram (2016) conducted a study to observe behaviour of soft soil under cyclic loads. They showed that, the best results are obtained when geocell is used with basal geosynthetic. Madhavi Latha (2011) presented a new finite element design method in order to construct embankments with geocells on soft ground using finite element method. The proposed method is compared with other design methods. A. Yildiz and Uysal (2015) analysed a test embankment sections which are constructed with and without PVT's. They also considered different material models including newly developed model which incorporates anisotropy of soft soil. Moghaddas Tafreshi and Norouzi (2015) conducted a research which tries to reduce settlements on road embankments by using shredded tire. They used different amount of shredded tire and different height of soil shredded mixture height. They compared the results with and without soil shredded tire mixture. Those methods can be listed as pre-consolidation of soft soil, using lighter material as a fill, replacing soft soil with another material or constructing vertical drains. However, all of those methods have shortcomings like time or geotechnical risks. In order to overcome those shortcomings basal reinforced piled embankments are used to construct embankments. Using reinforcements over piles decrease the pile cap area necessary to form soil arches which transfer embankment loads to piles. Reinforcement also transfers some part of the load to piles. Terzaghi explained soil arching as, when two adjacent soil exists and one yields, shear bands forms between yielding and the adjacent one. Shearing reduces stress over the yielding soil and transfers it to adjacent soil. In the study of Han and Gabr (2002) difference between coverage areas of piled fills and geosynthetic reinforced piled fills can be seen. Several researchers investigated effects of height embankment, tensile stiffness of geosynthetic and elastic modulus of pile, effect of pile length to calculated settlements, forces acting on piles, tension in geosynthetics and lateral deformation of embankment (Han and Gabr 2002, Bhasi and Rajagopal 2015). Effects of properties of soft soil, column and geosynthetic, construction speed of embankment, connection type of geosynthetic, pile wall spacing are also studied in the literature (Huang and Han 2010, Zhan *et al.* 2013, Liu and Rowe 2016). Some researchers conducted experiments to show formation of soil arches, load transfer mechanism from embankment to ground soil and piles and determined each load parts separately. Gathered information from experiments are used to modify analytical models (Van Eekelen 2012a, b).

Large scale tests are conducted to investigate the effect of existence of geogrid. Another study concerned about full scale investigation of an embankment. Settlements, lateral displacement, axial forces in piles, load distribution among the subsoil and caps and forces on geosynthetic are evaluated (Xing *et al.* 2014, Liu *et al.* 2007). Lai *et al.*

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(2014) demonstrated soil arching within geogrid-reinforced and unreinforced pile supported embankment by using discrete element method. Huang and Han (2009) also conducted 3D numerical analysis of reinforced deep mix column supported embankment. Zhang *et al.* (2012) and Ghosh (2016) developed new calculation method to calculate settlements of an reinforced pile embankments by using Winkler's foundation and Timoshenko's beam theory. Method developed by Ghosh (2016) *et al.* can be applied to two layer geosynthetics. Lu and Miao (2015) developed a new method to calculate stresses on pile cap and geosynthetic. During their study, authors considered membrane effect of geosynthetic and strenght of subsoil. Julian Lehn et. al. (2016) carried out a three dimensional numerical study by using finite element method in order to determine influence of cyclic loading in the arching mechanism which is developed in reinforced pile supported embankments. Some studies investigated design guideliness in order to determine their shortcomings and disadvantages of the design guideline. Several modifications are proposed to overcome those shortcomings and disadvantages (Van Eekelen 2016, 2011). Van Eekelen and Venmans (2016) compared traditional way of constructing embankment and reinforced pile supported embankment by means of economic aspects and geotechnical risks. After their assesment, construction of reinforced pile embankment is chosen. Some researchers compared different design methods with each other. Stress reduction ratio, geosynthetic strain and tension and pile efficacy were used to compare results from different design methods (Priyanath Ariyarathne and D.S. Liyanapathirana 2015, S.J.M. Van Eekelen *et al.* 2015). Wan-Huan Zhou *et al.* (2016) investigated soil arching mechanism on a railroad embankment using finite element method. Rui *et al.* (2016) conducted trapdoor experiments in order to observe development of soil arching and type soil arching. They considered different pile dimensions, different trapdoor width and different sand granulometer. Using particle image velocimetry, researchers determined development of soil arches for each case. Van Eekelen *et al.* (2012a, b) carried out a research consisted of two stages to measure and calculate forces transferred to piles, geosynthetics and subsoil support. At the first stage, researchers separately measured the forces from experiments. They also conducted a parametric study to reveal possible differences in geosynthetic types, usage of double layer biaxial geogrid without fill between, stiffness of geosynthetic. On the second part of the study, experimental results are compared with analytical result computed by EBGEO. Due to the difference, some modifications are proposed to EBGEO.

Main purpose of this paper is to investigate the effect of second layer of geosynthetic and the effect of traffic loading. However, second layer of the geosynthetic is not just laid inside the working platform, but also higher locations inside the embankment. Results are evaluated regarding settlements on natural soil, pile and surface of embankment along with excess pore water pressure development and dissipation on soft soil. Those results are compared with results computed by varying pile properties, reinforcement stiffness, embankment fill properties and properties of soft soil. Results of the models with and without application of traffic load are also compared. Plaxis finite element analysis platform is used throughout the study and effectiveness of second layer of reinforcement is discussed at the end of the study.

2. Material and method

A field study is selected from the literature to conduct parametric study afterwards. The study of Liu *et al.* (2007) is selected for this purpose. Selected study concerns about embankment construction over 2.3 m silty clay, 10.2 m soft silty clay, 2 m medium silty clay and sandy silt. Ground water level is determined at depth of 1.5 meter. Embankment constructed in 55 days and measurements for settlements and excess pore water pressures are continued for 180 days from the beginning of construction. Constructed embankment and places of instruments can be seen from Fig. 1. Constructed embankment consisted of 16 m pile with a diameter of 1m and 3D distance between adjacent piles. Reinforcement stiffness is selected as 1180 kN/m for the embankment construction. Embankment has 1V:1.5H side slopes. Other properties and results can be found on Liu *et al.* article.

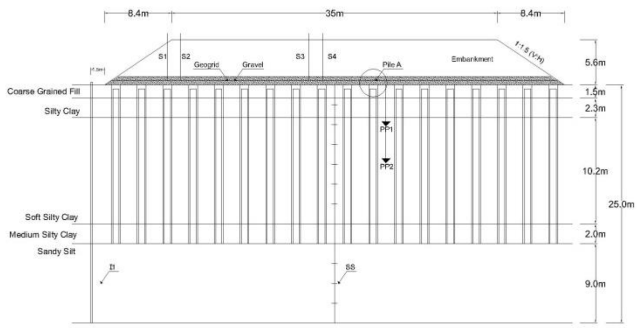
Four settlement plates are placed in order to measure settlements. They are named as S1, S2, S3 and S4. Two of them, S1 and S4 are located over a pile head while the other two, S2 and S3 are located on the subsoil. Ten pressure cells are placed around pile A. Settlement plates and pressure cells are installed surface of the foundation soil, just under the embankment fill. Two pore water pressure piezometers are installed at a depth of 4 meter and 8 meter midway between two piles near to the centre of the embankment. All of those instruments can also be seen in Fig. 1. Inclinometer I1 can also be seen in Fig. 1 which is placed to measure lateral deformation of embankment. The subsurface settlement gauges (SS) are also placed. However, researchers of this study are not interested in measurements of I1 and SS.

During the finite element method (FEM) modelling on Plaxis, Mohr-Coulomb material model is selected to model embankment fill, gravel and coarse grained soil layers. Layers of silty clay, soft silt clay and medium silty clay are modelled with soft soil model. Hardening soil model is applied to sandy silt layer. Model parameters for these layers for Plaxis can be seen in Table 1. Totally 38 finite element analysis is conducted for the purposes of this study.

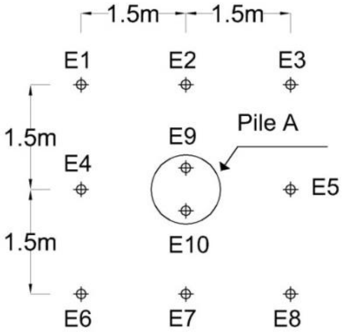
Internal angles of friction are not provided for the silty clay, soft silty clay, medium silty clay and sandy silt soil layers in the reference case. Therefore, they are calculated by using formula given below.

$$M = \frac{6\sin\phi}{3-\sin\phi} \tag{1}$$

Internal angles of friction of embankment, gravel and coarse grained fill are provided in the Liu *et al.*'s (2007) study. However, those internal angles of friction are converted to plane strain values by the formula used by Suliman B.A. Mohamed *et al.* (2014). The formula is given below.



(a) Cross section of modelled embankment



(b) Pressure measurement points around Pile A

Fig. 1 General information about modelled embankment

Table 1 Material model parameters for Plaxis

Material	Model	c (kPa)	Φ (°)	E (kPa)	ν	λ^*	κ^*	e_0	k_x (m/day)	k_y (m/day)
Embankment	MC	11	28	20000	0.3	-	-	-	129.6	86.4
Gravel	MC	11	43	20000	0.3	-	-	-	129.6	86.4
Coarse Grained Fill	MC	17	25	7000	0.3	-	-	-	129.6	86.4
Silty Clay	SSM	1	28	-	0.35	0.04	0.00727	0.65	1.3*10^{-4}	8.64*10^{-4}
Soft Silty Clay	SSM	1	19.3	-	0.35	0.07	0.014	1.17	6.48*10^{-4}	4.32*10^{-4}
Medium Silty Clay	SSM	1	24.5	-	0.35	0.03	0.00603	0.66	6.48*10^{-4}	4.32*10^{-4}
Sandy Silt	HSM	1	9.3	79710	0.35	-	-	0.78	6.48*10^{-4}	4.32*10^{-4}

Table 2 Comparison between field measurements and finite element model

	Field		FEM		Difference	(%)
	55th day	180th day	55th day	180th day	55th day	180th day
S1 mm	9	14.3	15.24	22.2	40.97	35.59
S2 mm	41	65	41.56	52.54	1.35	23.72
S3 mm	63	87	65.85	85.04	4.33	2.30
S4 mm	14	19	16.97	28.83	17.5	34.10
E4 kPa	31.4	38	37.8	39.5	16.93	3.80
E9 kPa	583.6	710	696.56	748.37	16.22	5.13

$$\phi_{ps} = \phi_{tx} - 17 \tag{2}$$

Elasticity modulus of sandy silt for the hardening soil model is calculated by the formula given below (Stein-Sturr).

$$E_{50} = \frac{15000 c_u}{I_p \%} \tag{3}$$

It should be remembered here that unconfined cohesion, liquid limit and plastic limits are given in the base project. Parameters controlling settlement and swelling behaviour in soft soil model is calculated by formulas (4) and (5) given below.

$$\lambda^* = \frac{\lambda}{1+e_0} \tag{4}$$

$$\kappa^* = \frac{\kappa}{1+e_0} \tag{5}$$

It should be noted that in the reference study, only void ratio under unit pressure is given. Therefore, initial void ratio should be determined for the Plaxis analysis. Initial void ratio is found by using void ratio under unit pressure by the given formula (Liu *et al.*).

$$e_0 = [(1+e) - (\lambda - \kappa)\ln 2 - \lambda \ln(\frac{2c_u}{M})] - 1 \tag{6}$$

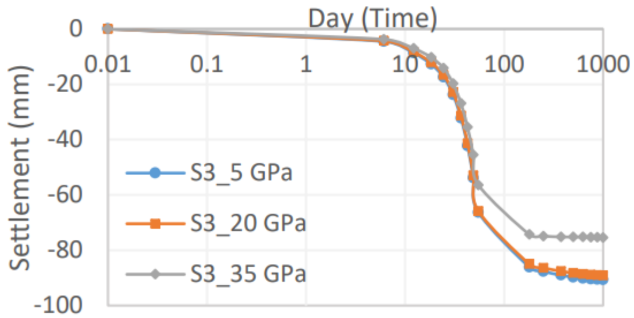
After the necessary material parameters are found out, reference project is modelled on Plaxis. The aim here is to decide if the finite element model is reflecting behaviour of construction or not. The measured values and calculated values are given in Table 2. Differences between measured values and calculated values are also given in percentage in Table 2.

Embankment is modelled in full scale with a 35-meter crest with. Total model width is chosen as 156 meter in order to prevent from the effects of boundary conditions to the results. The reference project model has 1853 elements. Those elements' average size is 1.61 meter. Number of elements and average size are kept constant unless geometry is changed. The lowest number of elements and the highest average size are given as 1438 and 2.08 meter respectively when soft soil layer thickness is 20.2 meter. The highest number of elements and the lowest average size is created for 6-meter soft soil thickness as 1938 and 1.46 meter. It should be noted here that, chosen elements are triangular elements with 15 nodes.

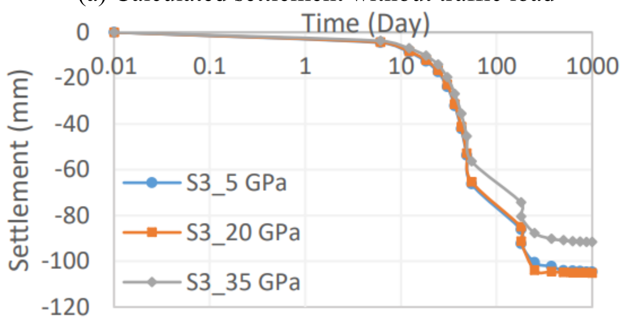
It can easily be seen that some of the calculations are closely matched with the results measured on field, while some are partially matched. After that parametric study is started. 12 kPa traffic load is applied to embankment to compare the behaviours of the embankment with and without traffic load acting over it. It should also be said that, finite element analysis concerned 1000 days from the beginning of the construction. Traffic load is exerted 180 days after beginning of embankment construction.

3. Results

Results are presented in this section beginning from the

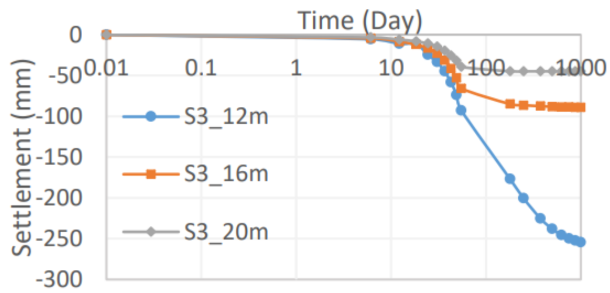


(a) Calculated settlement without traffic load

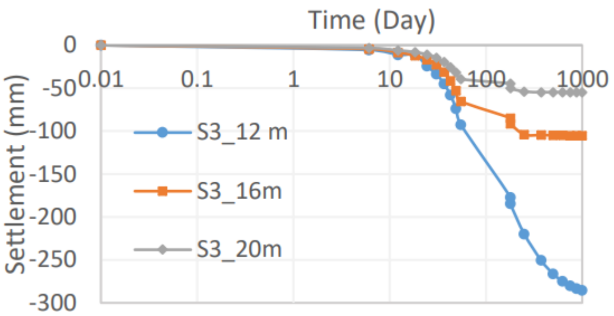


(b) Calculated settlement with traffic load

Fig. 2 Settlement-Time graphic of S3 depending on pile elasticity modulus



(a) Calculated settlement without traffic load



(b) Calculated settlement with traffic load

Fig. 3 Settlement-Time graphic of S3 depending on pile length

pile properties, reinforcement properties, embankment material properties and soft silty clay layer properties.

3.1 Effect of pile properties

This section covers effect of pile elasticity modulus, and pile length into results of settlements, pressures and excess pore water pressure.

3.1.1 Effect of pile elasticity modulus

Three finite element analysis is performed using three different pile elasticity modulus. Then these analyses are repeated to see the effect of traffic loading. 5 GPa, and 35 GPa are selected as an additional elasticity modulus to 20 GPa which is elasticity modulus of the piles constructed.

Change in Settlement

The smallest settlements are calculated for the highest pile elasticity modulus for all the time intervals considered in this study.13.09 mm, 19.39 mm and 21.04 mm settlement is computed on S1 for 35 GPa pile elasticity modulus at 55th, 180th and 1000th day respectively.

Settlement computed at S2, S3 and S4 are given as 47.20 mm, 75.47 mm and 26.81 mm on 1000th day for 35 GPa pile elasticity modulus. When the traffic load is applied to embankment, smaller change is seen for S1 and S4.

Settlements are increased to 23.85 mm, 53.29 mm, 91.57 mm and 31.96 mm for S1, S2, S3 and S4 after 1000 days.

Change and behaviour of settlement on S3 can be seen on Fig. 2. Sudden increase due to traffic load can also be seen on Fig. 2.

When differential settlement between S1-S2 and S4-S3 is investigated, it is seen that as the elasticity modulus of pile increases, differential settlement decreases. Decrease is more pronounced when elasticty modulus increases from 20 GPa to 35 GPa. Settlement difference is found as 26.16 mm and 48.66 mm between S1-S2 and S4-S3 respectively.

The lowest settlement on embankment settlement is also computed for 35 GPa pile elasticity modulus. It is computed as 85.14 mm without presence of traffic load at the end of

1000 day. Settlement on embankment surface is increased as 104.14 mm at the end of 1000 day when traaffic load is applied.

Change on pressure

Pressure acting on the pile head A does not change significantly. The highest pressure computed at pile A is computed 770.59 kPa without traffic load for 35 GPa pile elasticity modulus. There is only 3 kPa difference between the lowest and the highest pile head pressure. When the traffic load is applied, the highest pressure increases to 888.44 GPa for 35 GPa. Traffic load also increases difference between the lowest and highest pressure to 13 kPa.

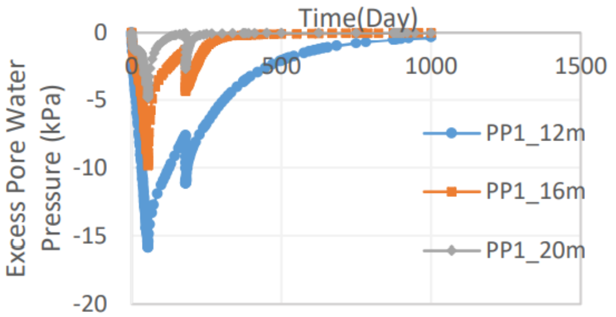
Change on excess pore water pressure

The highest excess pore water pressure is calculated when pile elasticity modulus is equal to 5 GPa. Excess pore water pressures are calculated as 10.10 kPa and 17.88 kPa for this case on PP1 and PP2. As the pile elasticity modulus is increased to 35 GPa, excess pore water pressures decrease to 7.89 kPa and 14.96 kPa. Application of traffic load increases excess pore water pressure as 3.12 kPa and 2.56 kPa for 5 GPa pile elasticity modulus. There is not significant change on excess pore water pressure increment due to traffic load as the elasticity modulus increases.

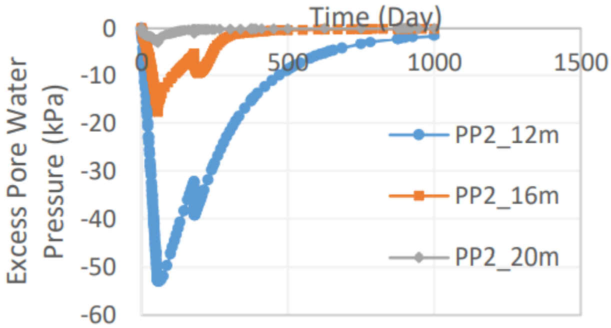
3.1.2 Effect of pile length

In addition to reference pile length of 16-meter, 12-meter and 20-meter pile length is also modelled during the study.

Pile diameter is kept constant and it is equal to 1 meter



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP2

Fig. 4 Variation of excess pore water pressure with respect to time depending on pile length

which is same as in the reference study. While 12-meter pile length behaves as frictional pile, 16-meter and 20-meter pile lengths act as end bearing pile.

Change on settlement

The lowest settlements are calculated when the 20-meter piles are used, because pile load is directly distributed to hard stratum. Therefore, the highest settlements are measured for 12-meter pile which transfers embankment load to soft soil by friction. When the settlement change is compared regarding days, it is seen that very little change is seen for 20-meter pile while the highest change is computed for 12-meter pile. The lowest settlements are computed as 2.89 mm, 24.12 mm, 44.93 mm and 2.90 mm for S1, S2, S3 and S4 respectively. Traffic load caused an increase of those settlements to 3.04 mm, 26.48 mm, 54.87 mm and 3.22 mm.

Change of settlement with respect to time and case are shown in Fig. 3.

Differential settlement increases as the pile length decreases for S1-S2 points. However, the highest differential settlement is observed for 16-meter pile length between S3-S4 points. The lowest differential settlements are computed as 21.23 mm and 42.03 mm respectively for 20-meter pile length.

Change on pressure

Pressure acting on E4 decreases as the pile length increases. The lowest pressure on E4 is calculated as 35.96 kPa, while the highest pressure is calculated as 46.43 kPa. Calculated pressure on E4 and E5 changed under 4 kPa except for 20 meter pile length when the traffic load is applied. Pressure acting over the pile slightly changes from 771.60 kPa to 767.16 kPa as the pile length increased from 12 meter to 20 meter. When the traffic load applied, calculated pressures increased 120.12 kPa and 106.5 kPa for 12 meter and 20 meter pile length.

Change on excess pore water pressure

Finite element analysis shows that, as pile length decreases, calculated maximum excess pore water pressure on 55th day increases, because higher embankment load is transferred to soft soil layer. The highest excess pore water pressures are calculated as 15.82 kPa and 52.79 kPa for 12-meter pile length, while it is calculated as 4.86 kPa and 3.09 kPa for 20-meter pile length at PP1 and PP2 respectively. Calculated excess pore water pressures dissipated to 7.63 and 0.08 kPa at PP1 and 32.26 kPa and 0.27 kPa at PP2 for 12-meter pile length and 20-meter pile length until traffic load is applied. When the traffic load is applied, excess pore water pressure increased to 11.07 kPa and 2.72 kPa at PP1, 37.74 kPa and 1.04 kPa at PP2 for 12 meter and 20-meter pile length. Excess pore water pressure behaviour can be seen on Fig. 4 given below for different pile length.

3.2 Effect of reinforcement properties

Effect of reinforcement's properties are divided into two groups. One group covers stiffness of reinforcement, while other group covers number of reinforcement.

3.2.1 Effect of reinforcement stiffness

In order to reveal effect of reinforcement stiffness to embankment behaviour, stiffer reinforcements are modelled on finite element code. Stiffness of reinforcement was selected as 1180 kN/m in the base considered in this study. Additional stiffness of 4000 kN/m and 10000 kN/m is selected for the parametric study.

Change in settlement

When effect of reinforcement stiffness is observed, it is generally seen that, as the reinforcement stiffness increased, computed settlement decreased. However, the lowest settlement on the top of the foundation soil is calculated for reinforcement stiffness of 10000 kN/m, while the lowest settlements of pile is calculated at the end of 1000 day are found as 22.23 mm, 47.69 mm, 73.04 mm and 28.37 mm for S1, S2, S3 and S4 respectively. It should also be mentioned here that, difference between settlements calculated for reinforcement stiffness of 4000 kN/m and 10000 kN/m is very low. The final lowest settlements are calculated as 24.05 mm, 52.84 mm, 87.04 mm and 32.77 mm when the traffic load is applied to embankment.

The lowest differential settlements are calculated for reinforcement stiffness of 10000 kN/m as 25.4 mm and 44.32 mm for S1-S2 and S3-S4 respectively.

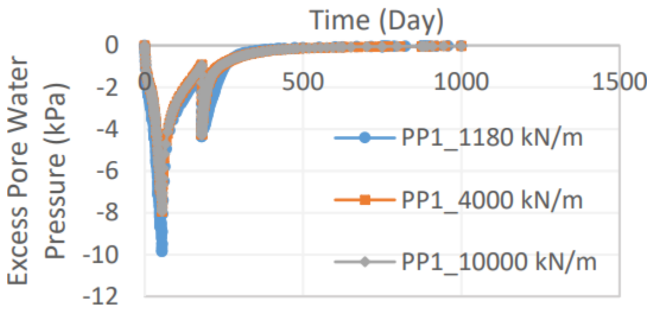
Settlement calculated on the embankment surface is changed between 99.82 mm and 80.86 mm as the reinforcement stiffness is increased from 1180 kN/m to 10000 kN/m. When the traffic load is applied, the lowest settlement is increased to 97.26 mm for reinforcement stiffness of 10000 kN/m at the end of 1000 day.

Change on Pressure

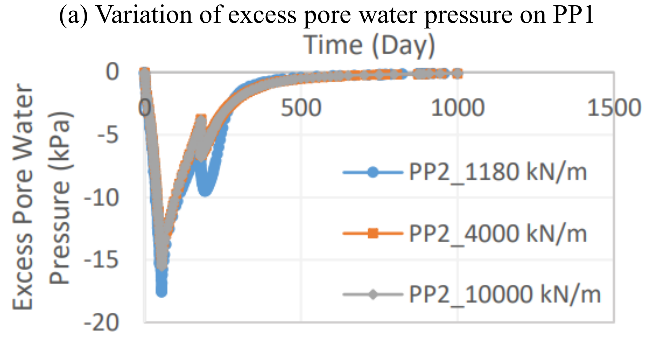
Pressure acting over E4 doesn't change significantly as the reinforcement stiffness increased. Similarly, pressure acting over E9 is changed between 769.52 kPa to 770.53 kPa as the reinforcement stiffness increased from 1180 kN/m to 10000 kN/m. When the traffic load is exerted to the embankment, on average 2 kPa pressure increase is computed at E4, while 3.2 kPa pressure increase is computed at E5 on average. Stress increase at E9 due to traffic load is changed between 115.62 kPa to 111.41 kPa as reinforcement stiffness increases.

Change on excess pore water pressure

The highest excess pore water pressure is calculated as 9.85 kPa and 17.57 kPa at PP1 and PP2 for 1180 kN/m reinforcement stiffness. As the reinforcement stiffness increased to 4000 kN/m, excess pore water pressure decreased to 7.93 kPa and 15.25 kPa. Further increase of reinforcement stiffness does not affect excess pore water pressure. When the traffic load is exerted on 180th day, excess pore water pressure increased to around 4.25 kPa at PP1 for all reinforcement stiffness values. Effect of reinforcement is more pronounced at PP2 under traffic load. Excess pore water pressure increased to 6.21 kPa for 4000 kN/m just after traffic load application. This value is slightly lower than the value calculated for 10000 kN/m reinforcement stiffness. However, when reinforcement stiffness is 1180 kN/m, calculated excess pore water pressure increased to 9.50 kPa and it requires more time to reach this value compared with other cases. Fig. 5 provides more information related to excess pore water pressure change with respect to different reinforcement stiffness. It can be said that, some amount of decrease on pore water pressure is seen when reinforcement stiffness is increased from 1180 kN/m to 4000 kN/m. However, very little change is computed when reinforcement stiffness increased to 10000 kN/m from 4000 kN/m. It is believed that, very small change would occur if the reinforcement stiffness is further increased.



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP2

Fig. 5 Variation of excess pore water pressure with respect to time depending on reinforcement stiffness

3.2.2 Effect of reinforcement number:

In order to determine effect of second layer of geosynthetic and make a comparison, second layer of geosynhetic is placed at different location inside the embankment. Those locations can be seen on Table 3.

Table 3 Placement pattern of reinforcements

Case	1st Reinforcement	2nd Reinforcement
1	0	0.25
2	0.25	0.5
3	0	0.5
4	0.25	2.42
5	0.25	2.95

Change in settlement

The lowest settlements are calculated for Case 3, while the highest settlements are calculated for Case 4 and Case 5. However, differences between Case 4 and Case 5 can practically be disregarded. Placing second layer geosynthetic like Case 3 can decrease settlement 16.90%, 14.68%, 17.79% and 14.09% at S1, S2, S3 and S4 respectively. Calculated settlements for different cases can be seen on Table 4. When the traffic load is applied to embankment, the lowest settlements are calculated for Case 3 too. 16.61%, 13.42%, 16.79% and 11.27% settlement decrease is calculated in comparison with reference case with traffic load.

Table 4 Calculated settlements for different cases after 1000 day from the beginning of embankment construction without presence of traffic load

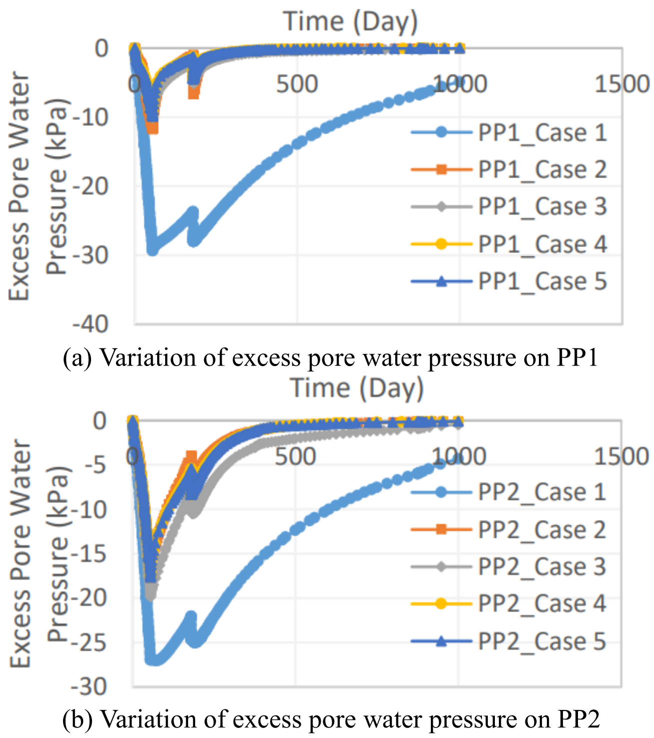
Case	S1 (mm)	S2 (mm)	S3 (mm)	S4 (mm)
1	22.07	53.09	74.34	26.50
2	22.61	65.82	75.95	34.05
3	20.80	48.06	73.29	27.01
4	24.98	56.35	88.70	31.46
5	24.98	56.34	88.97	31.40

When the settlement on embankment surface is considered, the lowest settlement is computed for Case 2 as 78.06 and highest settlement is computed as 100.48 mm for Case 4. When traffic load is applied, the computed lowest and highest settlements increased to 93.85 mm and 117.76 mm for Case 2 and Case 4.

The lowest differential settlement differs for S1-S2 and S3-S4 points. The lowest differential settlement on S1-S2 is seen on case 3 while, the lowest differential settlement is computed on case 2 for S3-S4. However, difference is only 4.4 mm between case 2 and case 3 for S3-S4. The lowest differential settlements are calculated as 27.26 mm and 41.9 mm for S1-S2 and S3-S4 respectively.

Change on pressure

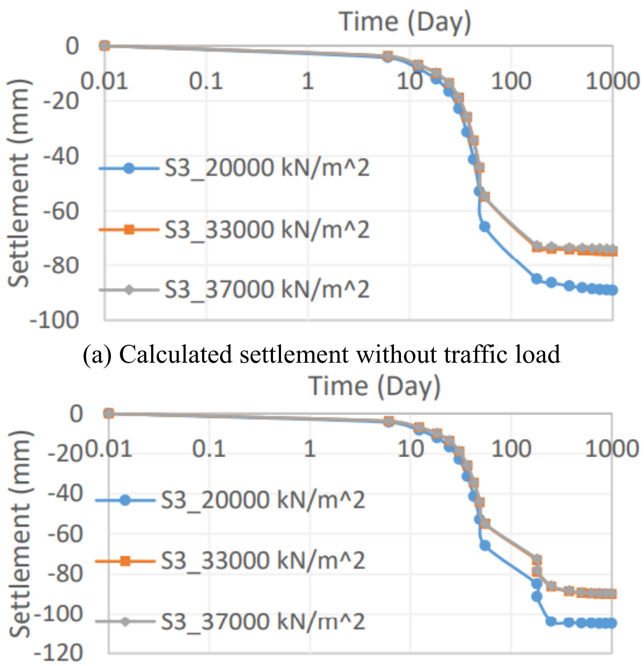
The lowest pressures on E4 and E5 and the highest pressure on E9 are calculated for Case 3. Calculated pressures are equal to 35.90 kPa, 20.96 kPa and 773.41 kPa without traffic load on E4, E5 and E9. When the traffic load is applied on embankment calculated pressure increases to 37.79 kPa, 24 kPa and 889.67 kPa for E4, E5 and E9 respectively.



(a) Variation of excess pore water pressure on PP1

(b) Variation of excess pore water pressure on PP2

Fig. 6 Excess pore water pressure-time graphic for different cases of reinforcement placement



(a) Calculated settlement without traffic load

(b) Calculated settlement with traffic load

Fig. 7 Settlement variation with respect to time depending on elasticity modulus of embankment

Change on excess pore water pressure

The highest excess pore water pressure is calculated for Case 1 as 29.35 kPa and 26.95 kPa for PP1 and PP2 respectively. The lowest excess pores water pressures are computed as 9.88 kPa and 17.61 kPa for PP1 and PP2 on Case 5. When traffic load is applied, the highest excess pore water pressures on Case 1 increased from 22.05 kPa and 24.20 kPa to 23.70 kPa and 27.72 kPa. The lowest excess pore water pressure increased to 4.38 kPa and 5.45 kPa from 1.31 kPa and 3.07 kPa for PP1 and PP2 respectively for Case 5. Change of excess pore water pressure can be seen on Fig. 6 for different placement of reinforcement.

3.3 Effect of embankment properties

3.3.1 Effect of elasticity modulus:

In addition to 20000 kN/m^2, 33000 kN/m^2 and 37000 kN/m^2 elasticity moduluses are selected to observe effect of different embankment elasticity modulus.

Change in settlement

The lowest settlements are calculated when the embankment elasticity modulus is selected as 37000 kN/m^2, while the highest settlements are calculated when elasticity modulus is selected as 20000 kN/m^2. The calculated lowest settlements are equal to 21.32 mm, 45.98 mm, 73.80 mm and 26.50 mm for S1, S2, S3 and S4 respectively at the end of 1000 day. When the traffic load is exerted immediate increase on settlements are seen and reach to 24.26 mm, 52.25 mm, 89.63 mm and 31.76 mm for S1, S2, S3 and S4 respectively. It should be noted that there is very little change calculated in settlements between 33000 kN/m^2 and 37000 kN/m^2. Change of settlement with respect to time can be seen in Fig. 7 for different elasticity modulus of embankment.

Differential settlements decrease as the embankment elasticity modulus increases. The lowest differential settlements are computed for 37000 kN/m^2 for S1-S2 and S3-S4 as 24.66 mm and 47.38 mm.

Settlements calculated on the embankment surface is varied between 99.82 mm and 80.16 mm when elasticity modulus is increased from 20000 kN/m^2 to 37000 kN/m^2. When the traffic load is exerted, settlements increase to 119.43 mm and 97.59 mm.

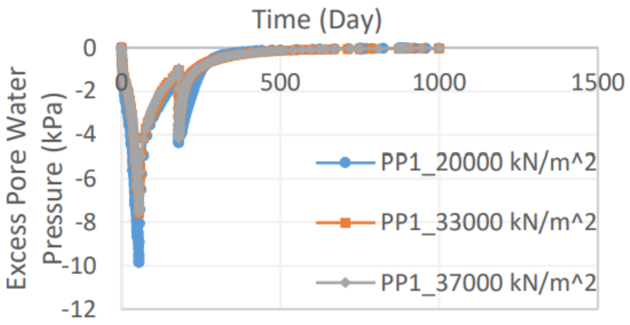
Change on pressure

Pressure acting over E4 is changing between 39.20 kPa and 34.82 kPa as the elasticity modulus increases from 20000 kN/m^2 to 37000 kN/m^2. Similarly, at E5, as the elasticity modulus increases pressure decreases from 32.90 kN/m^2 to 30.51 kN/m^2.

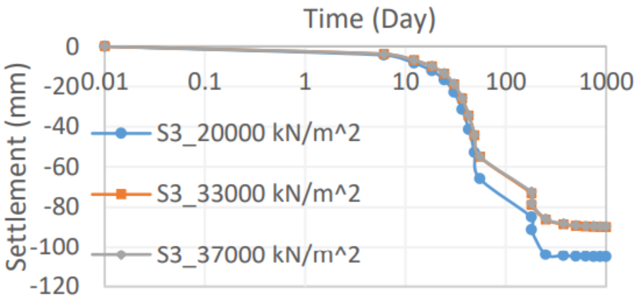
Pressure acting over E9 is increased with increasing elasticity modulus as expected. Pressure on E9 is calculated as 769.52 kPa for 20000 kN/m^2, while it is calculated as 804.65 kPa for 37000 kN/m^2. When the traffic load is applied to embankment crest, significant change does not occur on the pressures for E4 and E5 compared with E9. Pressure calculated on E9 increased to 885.14 kPa for 20000 kN/m^2, while it increased to 919.31 kN/m^2 for 37000 kN/m^2 elasticity modulus.

Change on excess pore water pressure

The highest excess pore water pressure is computed for 20000 kN/m^2 as 9.85 kPa and 17.57 kPa for PP1 and PP2. The computed highest excess pore water pressure decreases as the elasticity modulus increases, however there isn't significant difference on excess pore water pressure calculated for 33000 kN/m^2 and 37000 kN/m^2. As the traffic load is exerted to embankment, excess pore water pressure increases to 4.36 kPa and 7.98 kPa on PP1 and PP2 for 20000 kN/m^2. There still isn't significant difference on

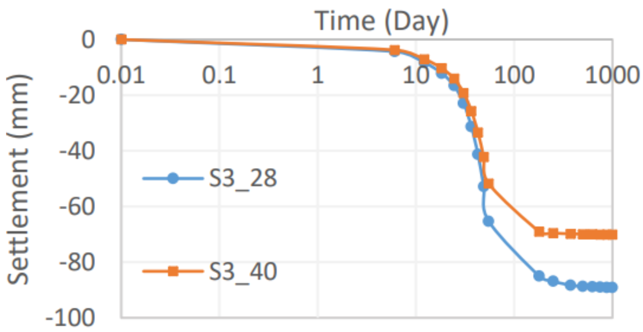


(a) Variation of excess pore water pressure on PP1

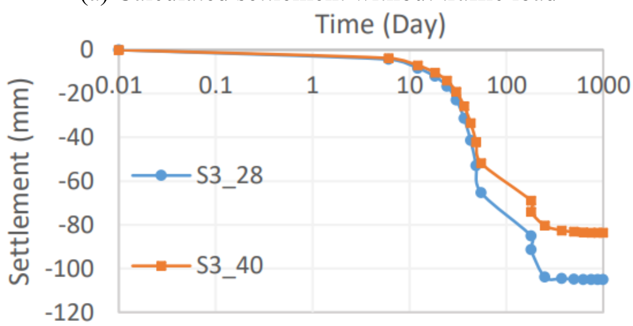


(b) Variation of excess pore water pressure on PP1

Fig. 8 Excess pore water-time graphic for different embankment elasticity modulus



(a) Calculated settlement without traffic load



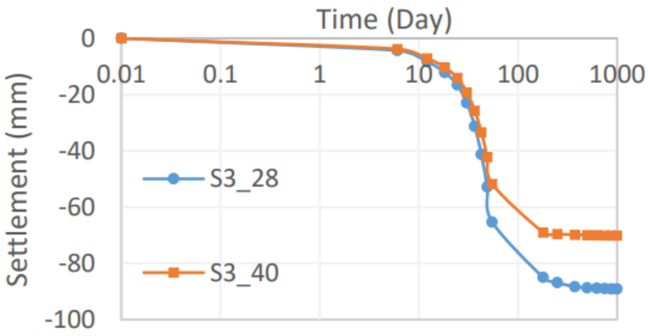
(b) Calculated settlement with traffic load

Fig. 9 Settlement variation with respect to time depending on internal angle of friction of embankment

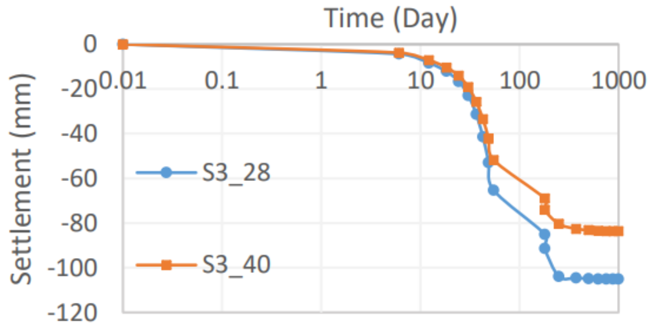
excess pore water pressure after traffic load computed for 33000 kN/m^2 and 37000 kN/m^2. Development and dissipation of pore water pressure can be seen on Fig. 8 with respect to different elasticity modulus of embankment.

3.3.2 Effect of angle of friction:

Change in settlement



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP1

Fig. 10 Excess pore water pressure time graphic for different internal angle of friction of embankment

Calculated settlement decreases as the internal angle of friction increases. It is also seen that increase in settlement between 55th and 180th day is almost equal for 28^o and 40^o angle of friction. However, increase in settlement is higher for 28^o angle of friction after 180th day till 1000th day. The lowest settlements are calculated as 21.37 mm, 46.06 mm, 70.18 mm and 27.68 mm on S1, S2, S3 and S4 respectively on 1000th day. When the traffic load is exerted to embankment, final settlements are calculated as 24.13 mm, 51.64 mm, 83.66 mm and 32.79 mm for S1, S2, S3 and S4 for 40^o angle of friction. Similarly, lower settlement on the embankment crest is calculated for 40^o angle of friction as 79.21 mm. It increases to 95.45 mm when the traffic load is applied. Settlement change on S3 can be seen on Fig 9 with respect to different angle of friction of embankment.

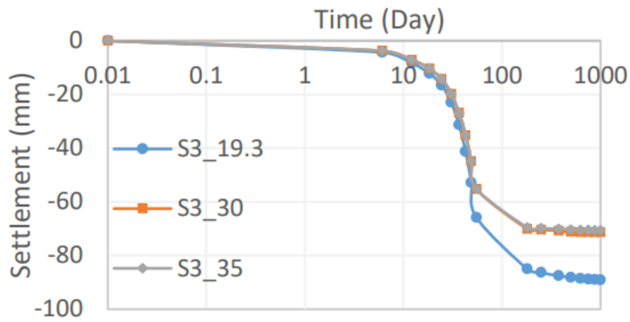
Differential settlement also decreases as the angle of friction of embankment fill increases. The lowest differential settlements are computed as 24.69 mm and 42.5 mm for S1-S2 and S3-S4 points respectively.

Change in pressure

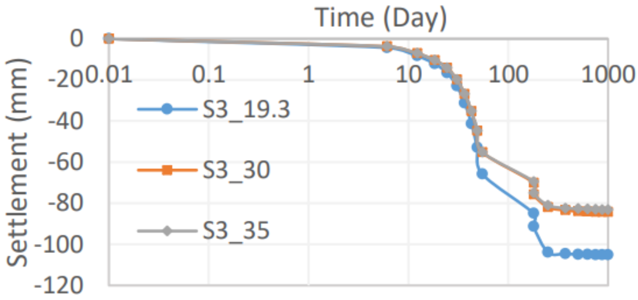
Pressure calculated on E4 decreases from 39.20 kPa to 32.33 kPa. Similarly, pressure on E5 decreased from 32.90 kPa to 30.65 kPa. As the angle of friction increased, pile force is also increased from 766.11 kPa to 797.82 kPa at the end of finite element analysis.

Change on excess pore water pressure

Smaller excess pore water pressure calculated when the angle of friction is higher. The highest excess pore water pressure is calculated on the 55th day for both PP1 and PP2. The highest excess pore water pressure decreases from 9.85 kPa to 7.79 kPa on PP1 and from 17.50 kPa to 15.37 kPa on PP2 as the angle of friction is increased from 28^o to 40^o. After completion of embankment construction, excess pore

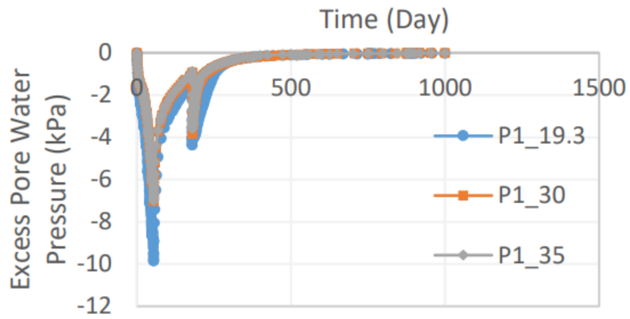


(a) Calculated settlement without traffic load

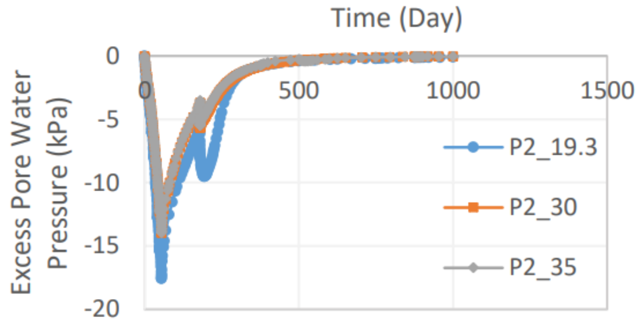


(b) Calculated settlement with traffic load

Fig. 11 Settlement variation with respect to time depending on internal angle of friction of soft soil



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP2

Fig. 12 Excess pore water pressure- time graphic for different internal angle of friction of soft soil

water pressure dissipated.

When traffic load is applied on the embankment on 180th day, excess pore water pressure increased immediately from 1.12 kPa to 3.336 kPa on PP1 and from 4.53 kPa to 6.40 kPa on PP2 for 40° angle of friction. After sudden increase in excess pore water pressure, it started to decrease just after following days. Development and dissipation of excess pore water pressure on PP1 and PP2 can be seen on Fig. 10 for different values of angle of friction of embankment.

3.4 Effect of soft soil properties

Effect of internal angle of friction, cohesion, thickness of soft soil layer is investigated on this section. Results are presented both for with and without presence of traffic load acting over embankment.

3.4.1 Effect of angle of friction

19.3°, 30° and 35° angle of friction is used during finite element computations and differences are determined to find effect of angle of friction of soft soil.

Change in settlement

As the angle of friction of soft soil causes decrease on settlements computed on S1, S2, S3 and S4. Settlement difference between 55th day and 1000th day gets smaller as the angle of friction increases. The smallest settlements are computed for 35° angle of friction. It is seen that settlements varied between 25.03 mm and 19.98 mm for S1, 56.33 mm and 45.31 mm for S2, 89.14 mm and 70.65 mm and 31.44 mm and 25.38 mm as the angle of friction is increased from 19.3° to 35°. When the traffic load presence in the finite element computation, calculated settlements increased to 26.97 mm, 61.40 mm, 105.14 mm and 35.76 mm for S1, S2, S3 and S4, for 19.3° angle of friction, while it increases to 21.44 mm, 49.61 mm, 83.15 mm and 29.14 mm on S1, S2, S3 and S4 for 35° angle of friction. Change of settlement on S3 with respect to time can be seen on Fig. 11 for different angle of friction of soft soil.

The lowest differential settlements are measured for 35° angle of friction. However, the difference is very low between computed values for 30° and 35° angle of friction. The lowest differential settlement is calculated as 25.33 mm and 45.27 mm for S1-S2 and S3-S4 respectively.

Change on pressure

There was not significant change on the pressures calculated on E4, E5 and E9 with respect to angle of friction of soft soil.

Change on excess pore water pressure

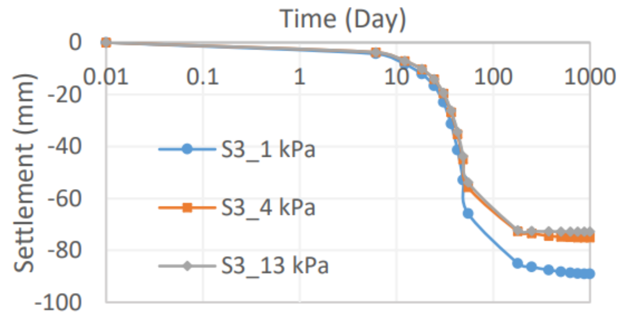
The highest excess pore water pressure is calculated as 9.85 kPa and 6.99 kPa on PP1 for 19.3 and 35° angle of friction. Excess pore water pressure is found as 17.57 kPa and 13.93 kPa on PP2 for 19.3° and 35° angle of friction. When results are compared, it is also seen that there is not significant difference when angle of friction is changed from 30° to 35°. The highest excess pore water pressure values are computed just after embankment construction is completed.

When traffic load is introduced to embankment, excess pore water pressure increased to 3.51 kPa from 0.89 kPa on PP1 and to 5.26 kPa from 3.53 kPa on PP2 for 35° angle of friction. Higher values are observed when angle of friction is lower. Fig. 12 shows behaviour of pore water pressure with respect to time and different angle of friction of soft soil layer.

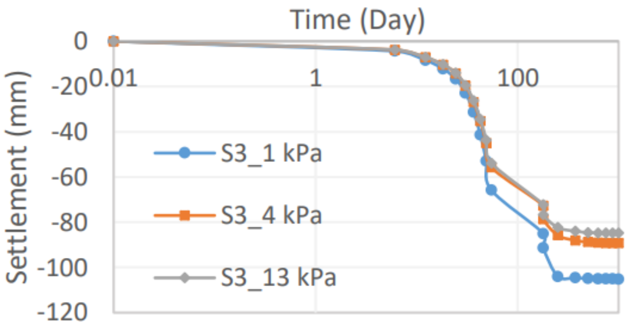
3.4.2 Effect cohesion

Change in settlement

As the cohesion increased from 1 kPa to 13 kPa,

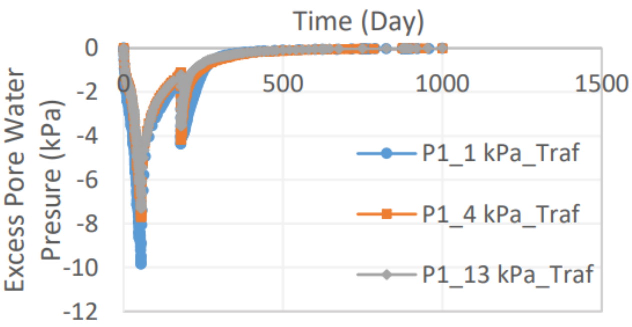


(a) Calculated settlement without traffic load

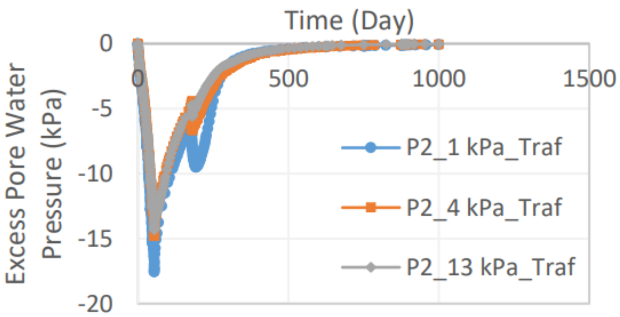


(b) Calculated settlement with traffic load

Fig. 13 Settlement variation with respect to time depending on cohesion of soft soil



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP1

Fig. 14 Variation of excess pore water pressure with respect to time depending on cohesion of soft soil

computed settlement decreases. The lowest settlements are computed as 21.02 mm, 46.61 mm, 72.86 mm and 27.43 mm for S1, S2, S3 and S4 for 13 kPa cohesion respectively at the end of finite element analysis. When the traffic load is applied to embankment, computed settlements are increased to 22.63 mm, 51.03 mm, 84.84 mm and 31.41 mm for 13 kPa cohesion at the end of finite element analysis.

Settlement on the embankment surface decreased from 99.82 mm to 82.22 mm as the cohesion increased from 1 kPa to 13 kPa.

When the traffic load is applied, embankment surface settlement increased to 119.43 mm and 96.87 mm for 1 kPa and 13 kpa respectively. Change of settlement with respect to time on S3 is depicted on Fig. 13 for different cohesion of soft soil layer.

As the cohesion of soft soil increases, differential settlements decrease. The lowest differential settlements are calculated as 25.59 mm and 45.43 mm on S1-S2 and S3-S4 points respectively.

Change on pressure

Pressure acting over E4 and E5 differs slightly for different cohesion value. Same behaviour is observed when traffic load is applied to embankment. Traffic load increases pressure 2.21 kPa on E4 and 3.05 kPa on E5 for 13 kPa cohesion. Pressure calculated on E9 increases more than 110 kPa for all cohesion values due to traffic load.

Change on excess pore water pressure

The highest excess pore water pressures calculated on th day from the beginning of construction of embankment. The highest excess pore water pressure is calculated as 9.85 kPa for 1 kPa cohesion. When the cohesion is increased to 13 kPa, excess pore water pressure decreases to 7.30 kPa on PP1. Similarly, maximum excess pore water pressure decreases to 14.32 kPa from 17.57 kPa when cohesion is increased from 1 kPa to 13 kPa.

As the time passes excess pore water pressure dissipates. It becomes 1.22 kPa on PP1 and 4.72 kPa on PP2 at 180th day of embankment construction for 13 kPa cohesion. When the traffic load applied to embankment at the same day, excess pore water pressure suddenly increases to 3.42 kPa and 5.58 kPa on PP1 and PP2.

Fig. 14 shows development and dissipation of excess pore water with respect to time under traffic load for PP1 and PP2 for different cohesion of soft soil.

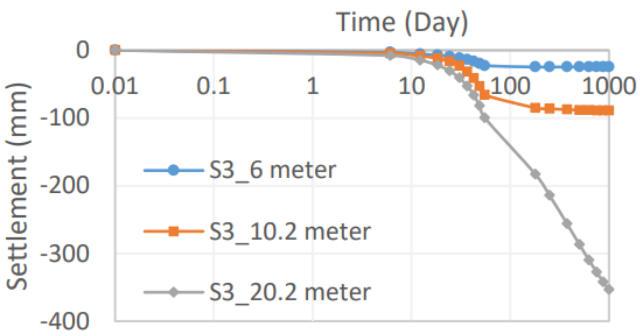
3.4.3 Effect soft soil layer thickness

In order to analyse the effect of thickness of soft soil layer, three different layer thickness selected as 6 meter, 10.2 meter, 20.2 meter. In order to reveal effect of traffic load, three different finite element analysis are conducted for each layer thickness.

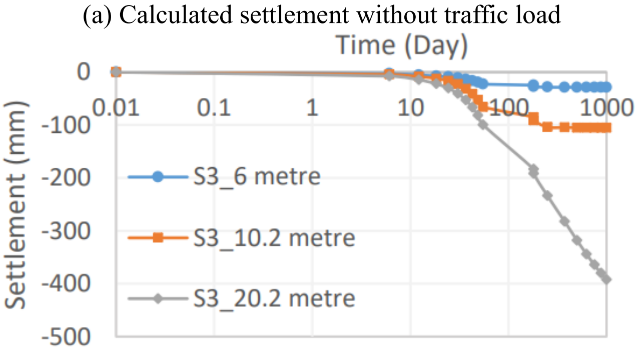
Change in settlement

The smallest settlements are calculated for thinner soft soil layer, while the highest settlements are calculated for 20.2-meter soft soil layer thickness. The lowest settlements are calculated as 3.17 mm, 27.98 mm, 24.70 mm and 3.77 mm on S1, S2, S3 and S4 at the end of finite element computation. The lowest settlement increments are also computed for 6-meter soft soil layer thickness. As the layer thickness increases, settlement increments also increase. Traffic load increases the lowest settlements to 3.41 mm, 31.03 mm, 28.70 mm and 4.60 mm for S1, S2, S3 and S4 respectively. Settlement increment is also gets higher as the thickness of the soft soil layer increases.

The lowest differential settlements are observed for 6-meter thickness layer. The differential settlements are computed as 24.81 mm and 20.93 mm for S2-S1 and S3-S4 respectively.

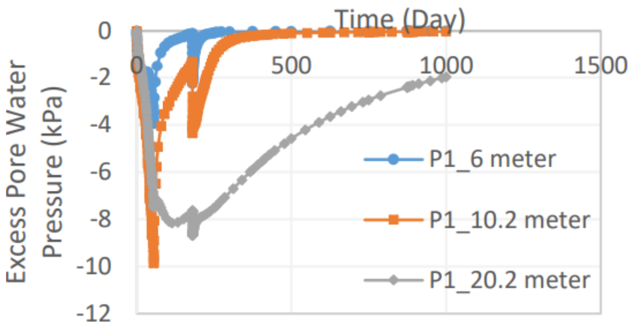


(a) Calculated settlement without traffic load

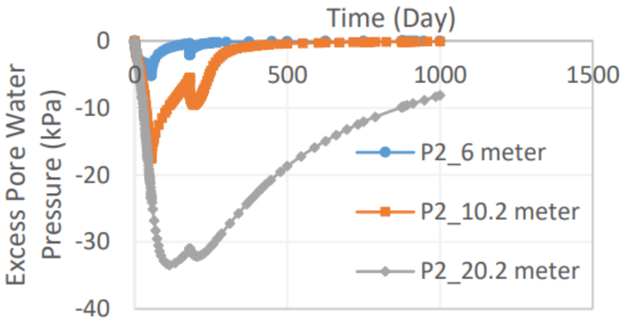


(b) Calculated settlement with traffic load

Fig. 15 Settlement variation with respect to time depending on thickness of soft soil



(a) Variation of excess pore water pressure on PP1



(b) Variation of excess pore water pressure on PP1

Fig. 16 Variation of excess pore water pressure with respect to time depending on thickness of soft soil

The smallest settlement is calculated for 6-meter soft soil layer thickness as 28.54 mm, while the highest settlement is calculated as 357.89 mm for 20.2-meter soft soil layer thickness. When the traffic load is exerted to embankment, settlements increase to 34.11 mm and 399.05 mm. Settlement change on S3 is depicted on Fig. 15 for different thickness of soft soil layer.

Change on pressure

Computed pressure increased from 24.02 kPa to 45.56 kPa when soft soil layer thickness increases from 6 meter to 20 meter. Pressure computed on E5 can be given as 30.65 kPa and 28.57 kPa on E5. Pressure acting on E9 changes between 783.49 kPa to 805.82 kPa when soft soil layer thickness is increased to 20.2 meter from 6 meter. When the traffic load is applied, pressure acting on E4 increases to 24.90 kPa and 48.84 kPa and 32.50 kPa and 28.74 kPa on E5. Pressure acting on E9 increased to 900 kPa and 919.93 kPa for 6 meter and 20.2-meter soft soil layer thickness.

Change on excess pore water pressure

The lowest excess pore water pressure is computed as 3.95 kPa on PP1 and 5.18 kPa on PP2 for 6-meter soft soil layer thickness. Those values are computed on 55th day of embankment construction. However, when the soft soil layer thickness increases to 20.2 meter, the highest excess pore water pressure is computed on the 55th day. Excess pore water pressure decreases to 0.11 kPa and 7.66 kPa on PP1 just before traffic load is applied for 6 meter and 20.2-meter soft soil layer thickness. Excess pore water pressures on PP2 decreases to 0.40 kPa and 31.08 kPa just before traffic load is applied. After traffic load is applied, excess pore water pressure suddenly increases to 2.25 kPa and 8.68 kPa on PP1 and 2.09 kPa and 32.14 kPa on PP2 for 6 meter and 20.2-meter soft soil layer thickness. Fig. 16 shows development of excess pore water pressure for PP1 and PP2 for different soft soil layer thickness.

4. Discussion

Settlements are decreased as elasticity modulus of pile increased, because as the stiffness difference between pile and soft soil increases, less load is transferred to soft soil. This behaviour also causes lower pore water pressure on soft soil.

When differential settlements are considered, it is seen that as the length of the pile decreases or soft soil layer thickness increases, lower differential settlements are calculated than more favourable conditions although settlements are higher. This behaviour can be explained by load transfer of piles. Since the loads carried by piles and the embankment are both transferred to soft soil layer, all the settlements increase. Because of this, lower differential settlements are observed for less favourable conditions for pile length and soft soil layer thickness.

As the length of piles are decreased, computed settlements are increased. When friction piles are used, it is seen that settlements increase enormously and seem to continue after 1000 days too. This is because of, although almost same pressure is calculated on piles; these loads are transferred to soft soil layer in case of friction piles. Due to this, excess pore water pressure also decreases as length of pile increases. Similar results are observed when thickness of soft soil layer is increased due to the same reasons.

Stiffness of reinforcement slightly effects computed settlement. As the stiffness increases measured settlements decreases, while pressure on E4 and E9 changes very slightly.

This can be attributed to deformation behaviour of reinforcement. Change in reinforcement stiffness also have some effect on dissipation required for excess pore water pressure.

When the two layer of reinforcement is used during construction of embankment, it is seen that in some cases produced better results than the reference case, some cases produced worse results than the reference case. This is due to that, in some cases, especially when reinforcements are placed closed to the piles; reinforcements make better contribution to load transfer mechanism rather than when they are placed away from the piles.

Embankment's elasticity modulus decreases settlements and excess pore water pressure and pressures acting over E4 and E5 because as it increases, more load is transferred to the pile which can be seen as pressure increase on E9. This behaviour shows us that, higher embankment elasticity modulus builds better soil arches in order to transfer more load to pile.

Increase of embankment's internal angle of friction contributes to form better soil arches which yields to better performance of embankment which means lower settlements and lower pressure on E4 and E5.

Increasing angle of friction of soft soil layer decreased computed settlements, excess pore water pressure and decreased pressure acting over pile. Researchers thinks this positive effect is not due to angle of friction's contribution to load transfer mechanism of embankment but increasing bearing capacity of soft soil. Increasing cohesion of soft soil also yields the same results and the reason of this is believed to be the same. However, researchers believe that, effect of cohesion is not reflected in this study correctly because, over consolidation ratio of soft soil layer is kept constant throughout the study.

5. Conclusions

Behaviour of basal reinforced is investigated in this study. A reference case is selected from the literature which provides detailed information on construction, instrumentation and measurements. This reference case is firstly modelled to calibrate the finite element model. After that, a parametric study is conducted. Pile elasticity modulus, pile length, stiffness of reinforcement, effect of second layer reinforcement and its place, elasticity modulus and angle of friction of embankment fill, angle of friction and cohesion of soft soil is considered during parametric study. Additional models are solved to reveal the effect of traffic load for all the cases stated above. Duration of analysis is chosen as 1000 days. Results of this study are summarized below.

Increasing elasticity modulus of pile decreases settlements without effecting pressure acting over pile. Higher pile elasticity modulus decreased computed excess pore water pressure.

When the pile tip is buried into firm soil layer, the lowest settlements, the lowest excess pore water pressures are computed, while the highest settlements and excess pore water pressures are computed for frictional piles.

Increasing reinforcement stiffness caused a decrease when it is increased from 1180 kN/m to 4000 kN/m, however further increase in reinforcement stiffness caused slight changes in settlements, pressures and excess pore water pressure

When two layers of reinforcement is used during embankment construction, the lowest settlements, pressures are computed for the third case except for S4 where it is calculated the lowest for case 1. However, at the case 1, excess pore water pressures are not completely dissipated therefore, increase of settlement on S4 is expected to be higher than case 3 when excess pore water pressure is completely dissipated. The highest settlements and pressures are computed for fourth and fifth case.

As the elasticity modulus of embankment is increased, computed settlements decreased. Lower pressure is calculated on E4 and E5 while higher pressure is computed on E9 as embankment elasticity modulus increased. Maximum excess pore water pressure decreased as elasticity modulus increased.

Increasing internal angle of friction of embankment causes decrease in settlement, pressures on E4 and E5 while it causes an increase on computed pressure on E9. Calculated excess pore water pressure also decreases with increase of embankment's angle of friction.

When the internal angle of friction of soft soil are increased, computed settlements decreases. Pressures computed on E4, E5 slightly differs according to angle of friction. Pressure computed on E9 decreases as the angle of friction of soft soil increases. Excess pore water pressure decreased on the initial increase, while it slightly changes for further increase.

Increasing cohesion of soft soil decreases settlements, excess pore water pressure. However, computed pressures E4, E5 and E9 are slightly differ for each different cohesion value.

The smallest settlements computed for thinner soft soil thickness. Pressure on E4 is also increased as thickness of soft soil increased, however pressure on E9 is almost constant. Excess pore water pressure is also decreased with decreasing soft soil thickness. For the 20.2-meter thickness case, it is pretty clear from Fig. 15 that amount of settlement is still increasing after 1000 day from the beginning of embankment construction.

Introduction of traffic load caused an increase in each parameter considered in this study. However, increase on settlements is very limited except for the cases where piles are used as frictional pile. Additionally, adding 12 kPa traffic load causes enormous increase on E9 for all cases.

When the friction pile is used, dissipation of pore water pressure takes more time than 1000 day.

Increasing pile elasticity modulus, pile length in case of end bearing piles, reinforcement stiffness, elasticity modulus and angle of friction of embankment, cohesion and angle of friction of soft soil layer decrease the differential settlement calculated at points S1-S2 and S3-S4.

Smaller settlements are computed for S1, S2, S3 and S4 on some cases than two-layer case. Those cases are angle of friction of soft soil, soft soil layer thickness and pile length for S1 while pile elasticity modulus, pile length, reinforcement stiffness, embankment elasticity modulus and angle of friction of embankment for S2. When S3 is taken into consideration, smaller settlements are computed by increasing reinforcement stiffness, with higher angle of friction of soft soil, cohesion of soft soil, soil layer thickness and pile length than using two-layer reinforcement. In the case of S4 smaller settlements are computed for higher elasticity modulus of pile, length of pile, elasticity modulus of embankment, angle of friction of soft soil and thickness of soft soil than two layer of reinforcement. Those shows us that, geotechnical engineer can consider increase material quality of or length of pile primarily, and then adding another layer of reinforcement.

It can be concluded that, constructing embankments by using piles and geosynthetics together yields lower settlements and faster construction of embankment.

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