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Effect of Prefabricated Vertical Drain System Properties on Embankment Behavior

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Abstract**—**This study presents the effect of prefabricated vertical drain system properties on embankment behavior by calculating the settlement, lateral displacement and induced excess pore pressure by numerical method. In order to investigate this behavior, three different prefabricated vertical drains have been simulated under an embankment. The finite element software PLAXIS has been carried out for analyzing the displacements and excess pore pressures. The results showed that the consolidation time and induced excess pore pressure are highly depended to the discharge capacity of the prefabricated vertical drain. The increase in the discharge capacity leads to decrease the consolidation process and the induced excess pore pressure. Moreover, it was seen that the vertical drains spacing does not have any significant effect on the consolidation time. However, the increase in the drains spacing would decrease the system stiffness.

Keywords**—**Vertical drain, prefabricated, consolidation, embankment.

I. Introduction

In the past few decades, vertical drain improvement techniques have been widely used in soft soil engineering, in order to accelerate the consolidation process of clay deposits significantly as a vertical drain shorten drainage path. Also, this system can improve the thick soft clays resistance combining with preloading which is considered to be a low cost solution [1]. Barron firstly, introduced the theoretical solution for the vertical drain [2]. Seed and Bookler proposed drainage techniques employing gravel drains to prevent liquefaction [3]. In an attempt to constitute more realistic models, along with the smear effect and well resistance, the latest studies have included several other factors, such as time dependent loadings, unsaturated soil condition and inhomogeneous permeability [4]-[6]. Due to the vertical drain system outperformance during earthquakes in Japan in 1990s, prefabricated vertical drains (PVD) have been used [7]. The behavior of installed PVDs and their effect on the consolidation were examined by several researchers [8]-[10]. Howell et al. presented centrifuge modeling of PVDs for liquefaction remediation. The results revealed that drains were effective in expediting the dissipation of excess pore water pressures and decreasing deformations [11]. Bahadori et al. evaluated the performance of soil improved with PVDs on reducing liquefaction potential using shaking table test. They found that the results demonstrate that PVDs have slightly better performance compared to gravel drainage columns at high relative density and high input acceleration. Also, they showed that by increasing the number and diameter of gravel and PVDs, deformations due to liquefaction are reduced [12].

Most of the aforementioned researches were based on the effect of vertical drains on the soil and they did not take into account the individual properties of PVDs effect on the consolidation. Given the diversity of results from previous research, more evaluation is required on the effect of the PVD system properties on embankment behavior. To attain the meaningful data, three different PVDs constructed beneath a rail way are operated. Then, the settlement and the lateral displacement are measured and compared with field results.

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II. Finite Element Modeling

A series of two dimensional finite element analyses was conducted in this study on an embankment constructed over two soft normally consolidated clays and two fill layers at the Sandgate Rail Grade Separation to investigate the effect of PVD system properties on embankment behavior [10]. The analysis was conducted using the finite element program PLAXIS software package. PLAXIS enables users handling a broad range of geotechnical problems such as excavation, slopes, tunnels and etc. The fill and soft normally consolidated clays layers were modeled using Mohr-Coulomb and modified Cam-clay failure criterion, respectively. The soil parameters for each layer are given in Table I [10]. In order to simulate the PVDs, four independent layers were modeled using Mohr-Coulomb failure criterion. The selected parameters for PVDs are given in Table II. The equivalent plane strain discharge capacity of PVDs calculated using (1) which is stated by [13]. For considering the smear zone effect, the diameter of the smear zone was considered three times of equivalent diameter of the drain.

$$q_{wp} = \frac{4k_h l^2}{3\frac{D^2}{4B}[\ln(\frac{D}{d_w}) + (\frac{k_h}{k_s} - 1)\ln(\frac{d_s}{d_w}) - \frac{3}{4} + \frac{2\pi l^2 k_h}{3q}] - 2B} \quad (1)$$

In this equation, q_{wp} is the plane strain discharge capacity, D is the diameter of unit cell, l is drainage length, B is the half spacing between drainage elements in plane strain analysis, q is the PVD discharge capacity, d_w is the drain diameter, k_h is horizontal hydraulic conductivity of the natural soil and k_s is the hydraulic conductivity of the smear zone.

TABLE I
SOIL PARAMETERS FOR EACH LAYER [10]

Soil layer	Model	Depth (m)	ϕ (degree)	c (kPa)	γ_{dry} (kN/m^3)	k_h (10^{-4} m/day)	k_v (10^{-4} m/day)
1	M-C	0-0.3	50	5	15	10	10
2	M-C	0.3-1.3	29	29	7.9	1.4	0.7
3	C-C	1.3-11.3	25	10	7.9	1.4	0.7
4	C-C	11.3-21.3	20	15	8.46	1.5	0.75

TABLE II
PVDS PROPERTIES

Case	Width (mm)	Thickness (mm)	Spacing (m)	Discharge capacity, q_w(m^3/year)	Unit weight (gr/m^2)	Dimension of mandrel (mm^2)
Case 1	2.5	100	2	100	100	120
Case 2	2.5	100	2	200	100	120
Case 3	2.5	100	2	400	100	120

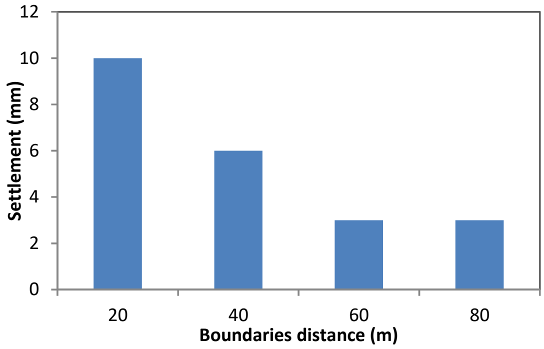

Fig. 1 The effect of distance from model boundary on the maximum ground settlement

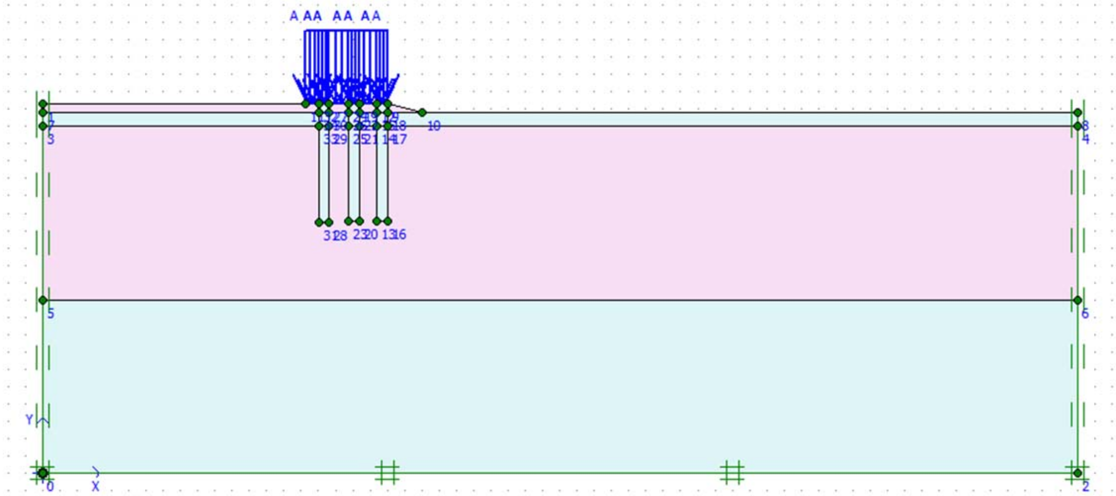

Fig. 2 Final finite element model

The train axle load was chosen in accordance with AS 1085.14-1997 code which provides an empirical method to calculate applied load. According to this method, the equal static pressure 150 kPa for low train speed were applied on the railway. For evaluating the boundary effect, a series of sensitivity analysis was conducted with 20 m, 40 m, 60 m and 80 m from the railway and the maximum railway settlement was measured. The obtained results are illustrated in Fig. 1. It can be seen that, if the boundary distance from the railway 60 m, the analysis results showed an acceptable level of accuracy. Also, the sensitivity analysis was conducted in order to investigate the mesh size. Three medium, fine and very fine mesh sizes were selected. The results indicate that the mesh size finer than the fine, has no influence on the numerical results. The final 2D plane-strain finite element model meshing and boundaries configuration is shown in Fig. 2.

III. RESULTS AND DISCUSSION

In this section, the effect of three different PVD system behavior was evaluated. The difference between three systems was the thickness, width and discharge capacity. Moreover, in order to validate the numerical results, the obtained results are compared with field data measured at Sandgate Rail Grade Separation [10].

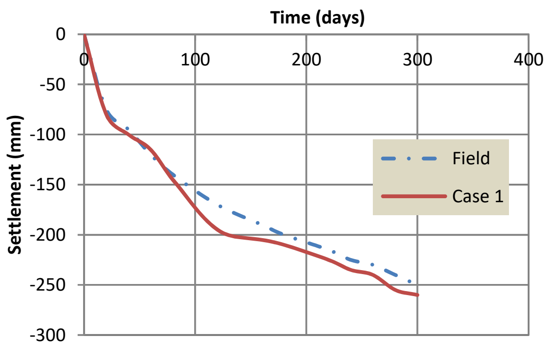

Fig. 3 The estimated and measured settlement versus time results at the center of railway

Fig. 3 shows the estimated and measured settlement versus time results at the center of railway. It can be seen that there is a good agreement between the estimated settlement for Case 1 and the field measured settlement. The obtained settlement for three different cases is given in Fig. 4. It can be inferred from this graph that Case 3 has the lowest consolidation time. It is observed that 80% consolidation due to the vertical drainages is occurred within at 100 days. On the other hand, it will take up to 160 days and 250 days to approach 80% for Case 2 and Case 1, respectively.

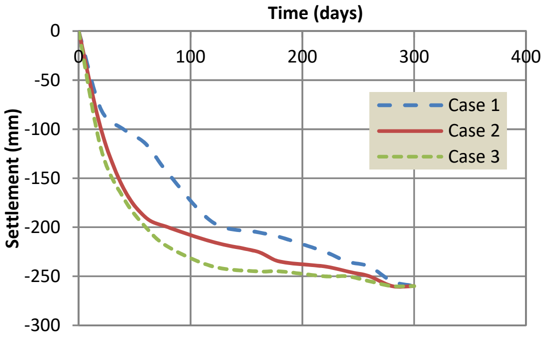

Fig. 4 Estimated settlements for three different cases

Fig. 5 illustrates the maximum lateral displacement of the ground occurred in the consolidation process along the model depth. It can be observed that there is not any significant difference between the three vertical drains lateral displacement. So it can be stated that the drainage properties do not affect the maximum lateral displacement magnitude. However, the maximum lateral displacement of Case 1, Case 2 and Case 3 occurred at 190 days, 85 days and 40 days after the end of the construction.

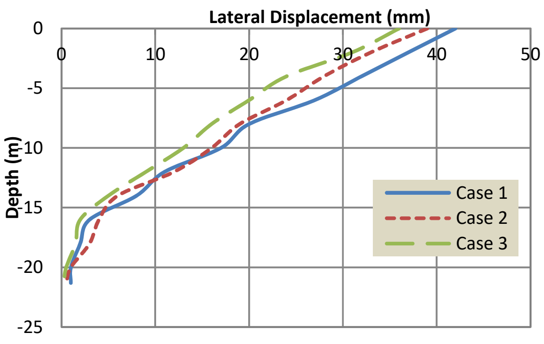

Fig. 5 Maximum lateral displacement of the ground occurred in the consolidation process

In order to investigate the effect of drains spacing on the lateral and vertical displacement of the embankment, the spacing between the vertical drains was increased. Fig. 6 compares the maximum lateral for 2 m and 4 m drain spacing. Also, Fig. 7 illustrates the vertical displacement for 2 m and 4 m spacing for Case 1 versus time. It can be inferred that, increasing the drain spacing has a significant effect on the lateral displacement, which leads to 20% higher displacement. Conversely, there is no significant difference between the maximum occurred settlements by increasing the drain spacing.

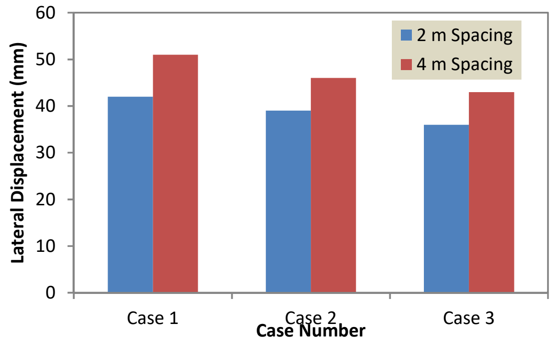

Fig. 6 Maximum lateral displacement for 2 m and 4 m spacing

Fig. 8 illustrates the induced excess pore pressure at the middle of first layer versus time for three different vertical drain cases. As was expected, Case 3 with the highest discharge capacity dissipates the excess pore pressure.

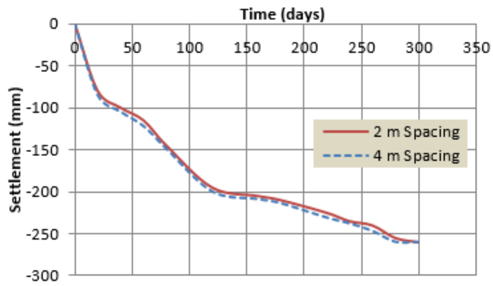

Fig. 7 vertical displacement for 2 and 4 m spacing

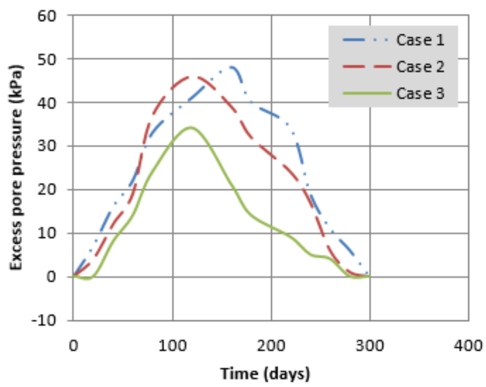

Fig. 8 Induced excess pore pressure at the middle of first layer versus time for three different vertical drain cases

IV. Conclusion

In this study, the effect of PVD system properties on embankment behavior has been evaluated using PLAXIS software. The obtained results indicate that the increase in discharge capacity has a significant effect on the consolidation time and induced excess pore pressure. The higher discharge capacity leads to decrease in the consolidation process and the induced excess pore pressure. Furthermore, it was observed that the discharge capacity does not have any influence on the lateral displacement of the soil. On the other hand, increasing the vertical drain spacing leads to higher lateral displacement due to the stiffness reduction of the vertical drain system. However, there was trivial difference between embankment settlements for different spacing.

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