EVALUATION OF FIELD PERFORMANCE OF PREFABRICATED VERTICAL DRAINS (PVD) FOR SOIL GROUND IMPROVEMENT IN THE SOUTHERN VIETNAM

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Abstract

A 40,000-km^2 soft ground area in the southern Vietnam is big obstruction for infrastructure development in Vietnam. PVD is the most popular technique applied to improve soft ground in the southern Vietnam. However, field performance of PVD based on field monitoring is quite discrepant from prediction. This study aims at better understanding of PVD field performance via case studies. The two complete projects using PVD for soft ground improvement were utilized for back analysis. Field monitored settlements agree well with predicted settlements when the field settlement has experienced a settlement of 0.3 m or less. The predicted settlement exceeds the field monitored settlement about 50% when the field settlement reaches 0.5 m or larger. The result indicates that degree of filed consolidation was less than 90%, and large field settlement keeps occurring during the service stage of highway embankments and may cause field settlement over the allowable settlement according to the Vietnam Code for soft ground improvement.

Keywords: Consolidation, Highway embankment, Prefabricated vertical drain (PVD), Preload settlement, Soft ground, Wick drain

Introduction

The Southern Vietnam, a 40,000-km2 area, lies on thick soft deposit. This soft deposit causes great difficulty for infrastructure development. Various soft ground improvement technologies have been applied in Vietnam such as vertical drain (sandy drain or wick drain), stone columns, and geotextiles. Prefabricated vertical drain (PVD) is applied widely in Vietnam since 1990s due to its advantages such as low cost, fast installation, safe for environment, and stable supply. However, several projects that PVD was used as a major soft ground improvement technique to improve soft deposit in the South have excess settlement in short time after the projects in service.

Field performance of PVD affects by a number of factors such as deformation, lateral pressure, infiltration, smear zone effects, and so on (Tran-Nguyen et al. 2010, Tran-Nguyen 2010, Tran-Nguyen & Edil 2011). Tran-Nguyen et al. (2010) and Ali (1991) reported that the discharge capacity of PVD reduce significantly when the PVD has experienced a percent settlement of 30% or more. Smear zone which is disturbed zone surrounding a PVD after installation using a mandrel delays horizontal consolidation process due to lower hydraulic conductivity of the smear zone than that of undisturbed zone (Tran-Nguyen & Edil 2011, Tran-Nguyen 2010). PVD discharge capacity decreases remarkably under a lateral pressure of 150 kPa or more (Rixner et al. 1986), that is, with long PVD (e.g., longer 20 m, Hansbo 1981), the PVD performance is affected by lateral pressure.

Bergado et al. (1996b) proposed that PVD discharge capacity should take a factor of safety of 2 or greater to take infiltration into account.

The Vietnam code for the use of PVD, 22 TCN 244-98 issued by Ministry of Transport (1998) assumed ideal performance of PVD, that is, all factors affecting the field performance of PVD are ignored. Consequently, prediction of consolidation settlement may be different from monitoring field settlement. This paper investigated two complete projects that used PVD to improve soft ground for back analysis.

Methodology

Prediction of consolidation settlement was analyzed using 22 TCN 244-98 which is the Hansbo (1979)'s theory and the Finite Element Method (FEM) (Plaxis 2D v.85. software) to compare with field monitored settlement.

Primary Consolidation Settlement

Consolidation settlement, S_c, is analyzed using Equation (1) and (2) depending on OCR – over-consolidation ratio.

If OCR = 1,

$$S_c = \frac{H_o}{1+e_0^o} C_c \log \frac{\Delta\sigma + \sigma_{vo}}{\sigma_{vo}} \tag{1}$$

If OCR > 1,

$$S_c = \frac{H_o}{1+e_0} \left[C_r \log \frac{\sigma_c}{\sigma_{vo}} + C_c \log \frac{\Delta\sigma + \sigma_{vo}}{\sigma_c} \right] \tag{2}$$

where H_o – thickness of soil in active zone, e_o – initial void ratio, C_c – compression index, C_r - Swelling index, σ_c – pre-consolidation pressure, σ_{vo} – overburden stress, $\Delta\sigma$ – embankment load or surcharge or preload.

Time Settlement by the Hansbo's Theory (1979)

Consolidation settlement at time t, S_t, is determined using Equation (3)

$$S_t = S_c.U_t \tag{3}$$

where U_t – average horizontal degree of consolidation at time t. By assuming ideal performance of PVD, U_t can be computed by Equation (4) (Hansbo 1979)

$$U_h = 1 - \exp\{-8T_h / F(n)\} \tag{4}$$

where T_h – time factor, $T_h = C_h.t/D^2_e$, D_e – diameter of an influence/drainage zone surrounding a PVD, $D_e = 1.13.S$, or $= 1.05.S$, for square or triangular pattern installation, respectively, S – distance between PVD, C_h – horizontal coefficient of consolidation, $F(n)=ln(n)- 3/4$ (Hansbo 1979) - spacing factor, $n = D_e/d_w$; $d_w=(a+b)/2$ - equivalent diameter of a PVD (Rixner et al. 1986), a – PVD thickness, b – PVD width.

FEM

In order to utilize the FEM to simulate PVD using the Plaxis 2D version 8.5 software, PVD needs to be converted into equivalent elements. There several ways to simulate PVD elements for the 2D FEM (Chai et al. 2001, Indraratna & Redana 2000), and this study uses two methods for comparison. The Mohr-Coulomb model was applied to simulate the behavior of the subsoil underneath the highway embankment. The Mohr-Coulomb model is popular to simulate for soft ground at acceptable accuracy to compare with more robust soft ground models such as modified Cam Clay model. To increase presision, 2D 15-node triangular elements were applied for FEM meshes. Considering a PVD as an equivalent element converted from an axisymmetric model to a plane strain model (Indraratna & Redana 2000) (FEM-1), and equivalent hydraulic conductivity of a PVD element, k_{hp}, can be defined as Equation (5).

$$k_{hp} = \frac{0.67}{\left[\ln(n) - 0.75\right]} k_h \tag{5}$$

where k_h – horizontal hydraulic conductivity of subsoil.

Alternatively, Chai et al. (2001) proposed a simple method to simulate the whole subsoil underneath an embankment improved using PVD (FEM-2). They suggested an equivalent vertical hydraulic conductivity for both the PVD and the subsoil, k_{ve}, defined by Equation (6).

$$k_{ve} = \left(1 + \frac{2.26.l^2}{F.D_e^2} \frac{k_h}{k_v}\right) k_v \tag{6}$$

where k_h, k_v – horizontal, vertical hydraulic conductivity of soil surrounding PVD, respectively, l – vertical drainage length, $F = F(n)$ – spacing factor.

Selected Case Histories

Saigon East-West Highway

Saigon East-West Highway which is a highway with two 50-m-wide embankments for the two directions crosses Ho Chi Minh City from the East to the West of the City with the total length of 22 km on soft ground areas (Figure 1). Embankment high of the highway is from 2 to 6 m and several techniques used to improve soft ground for the 22-km-long highway embankment. A research location is at km 17 + 320 on a section that soft ground was improved using PVD. The cross-section at this location is shown on Figure 2. Soil properties of the selected location are printed in Table 1. Along the 50-m subsoil profile at km 17 + 320, there are 3 layers: (1) a 15-m very soft clay layer at the top with SPT around 0-2 blows, (2) a 6-m medium stiff clay layer, and (3) fine loose sand layer at the bottom. It is noted that the authors obtained all soil properties from the contractors.

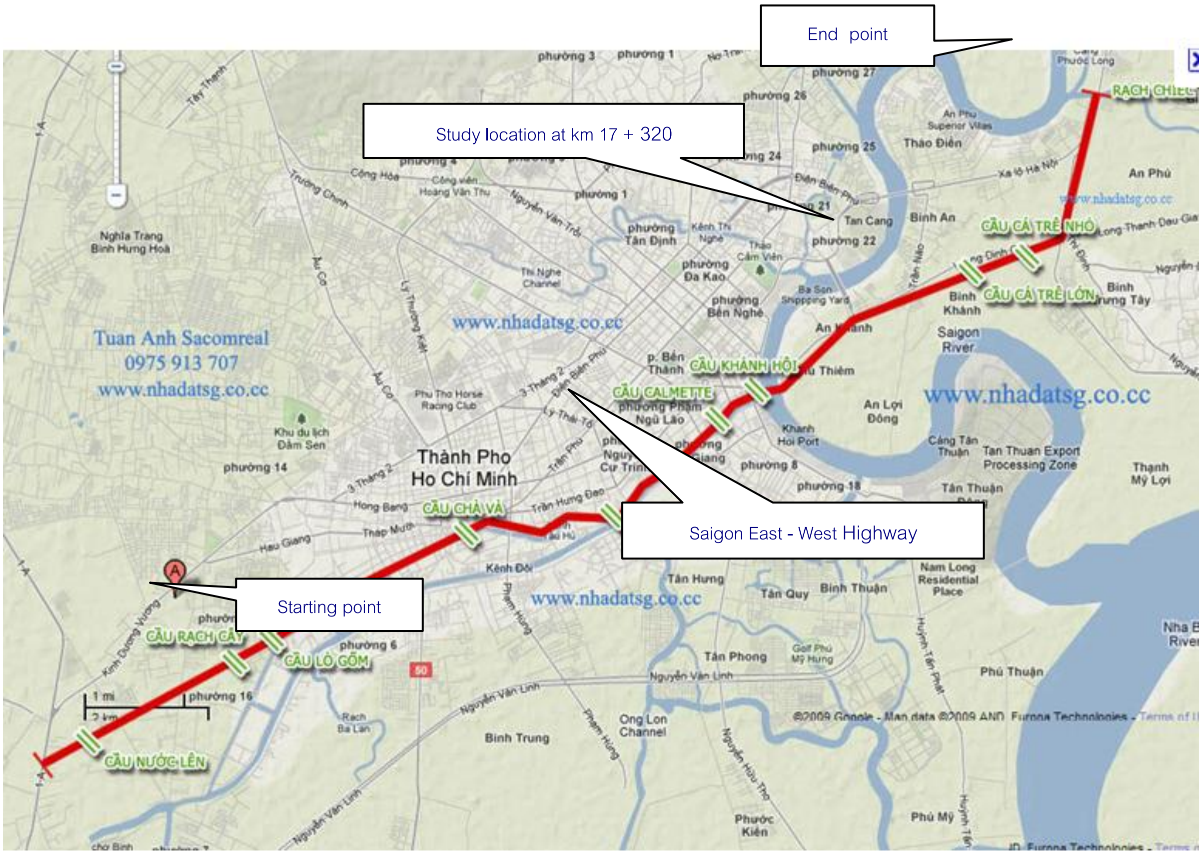

Figure 1. The Saigon east-west highway and study location at km 17 + 320 in Ho Chi Minh City (Google map)

Chikami PVD (A6) made by Japan (100 x 4 mm) was used at this location with PVD length of 21.5 m installed in square pattern at a distance of 1.2 m. The PVD discharge capacity was 1000 m^3/year.

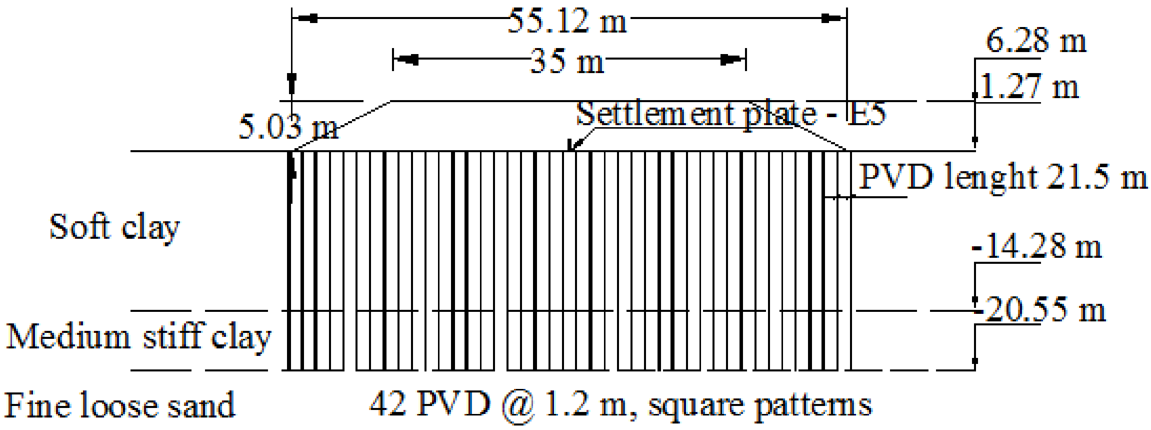

Figure 2. A selected section at km 17 + 320 on the Saigon East-West highway in Ho Chi Minh City

Table 1. Soil Properties at the Study Location km 37 + 320 on the Saigon East-West Highway, Ho Chi Minh City

Layer	Thick-ness	γ	E	v	φ	c	k_v	k_h
	m	kN/m³	kN/m^2		(^{o})	kN/m²	m/day	m/day
Very Soft clay	15.5	14.5	1160	0.35	9.08	8.8	1.21E-04	3.63E-04
Medium stiff clay	6.3	15.4	1340	0.3	8.10	8.8	1.47E-05	4.41E-05
Fine loose sand	> 15	19.2	1580	0.3	10.30	7.2	2.76E-05	3.10E-05

Field monitored settlement was obtained via the settlement plate E5 located at the centerline of the embankment (Figure 2). The surcharge was divided into two main stages with several minor surcharge stages between the first and the last surcharge stage. The first fill height was 1.3 m and maintained in 446 days. Several fill steps were conducted to raise up to a maximum height of 5.03 m in about 300 days, and the highest fill was kept until the 1019th day with the total accumulated settlement of 2.2 m. Figure 3 shows the field monitored accumulated settlement at the study location, km 17 + 320.

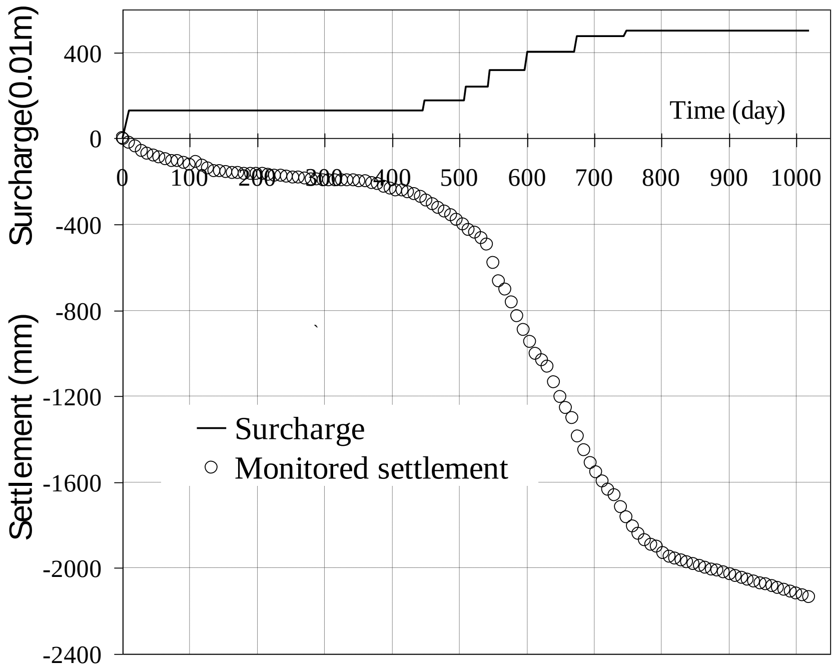

Figure 3. Field monitored settlement for 1019 days at the maximum height of 5.03 m.

The settlement varying with time was computed using Hansbo (1979) (or 22 TCN 244-98) (Eqn. 1,2,3,4), FEM-1 (Eqn. 5), and FEM-2 (Eqn. 6). The Mohr-Coulomb model was utilized to simulate the subsoil behavior in the Plaxis 2D v8.5 software. Figure 3a and Figure 3b demonstrate FEM meshes using Plaxis 2D v8.5 for FEM-1 and FEM-2 respectively, The result is shown in Figure 4.

It can be seen that the computed settlements were significantly diverged from the monitored settlement at large consolidation settlement (e.g., S_t >= 0.3 m). In order words, the assumption of the ideal performance of PVD is not relevant for large consolidation settlement.

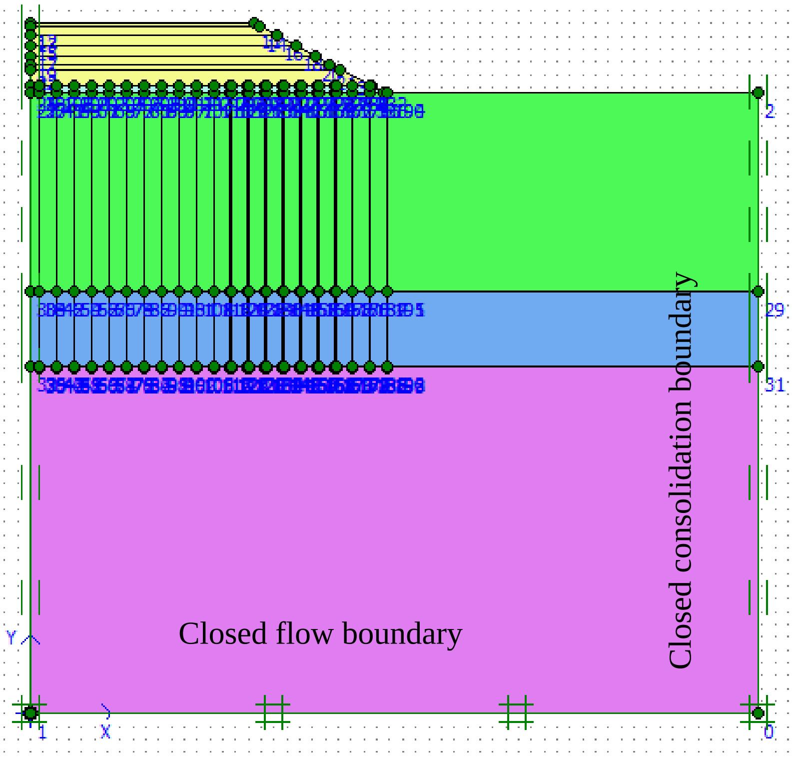

Figure 3a. A FEM-1 mesh for the initial conditions using the PLAXIS 2D software

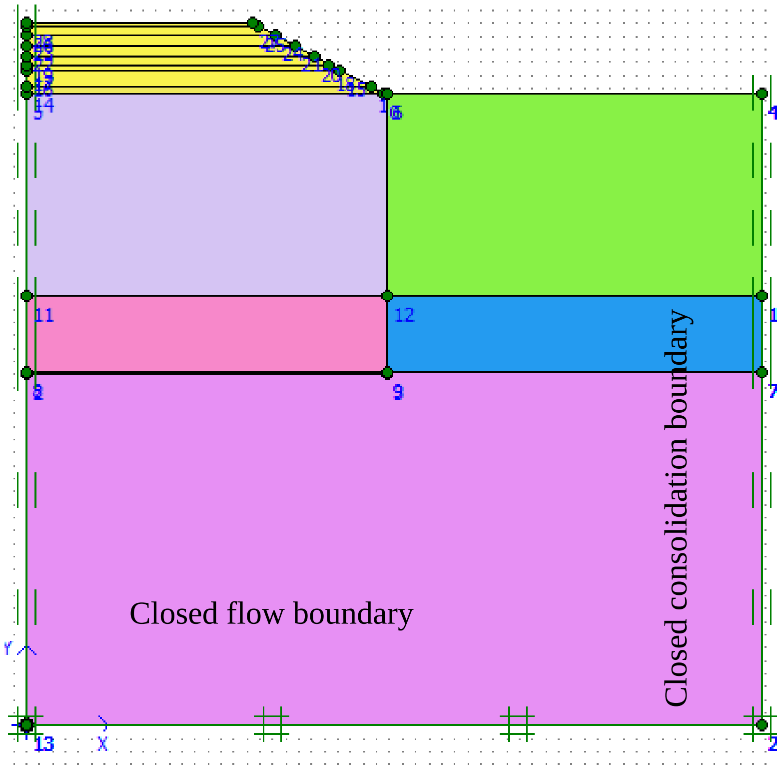

Figure 3b. A FEM-2 mesh for the initial conditions using the PLAXIS 2D software

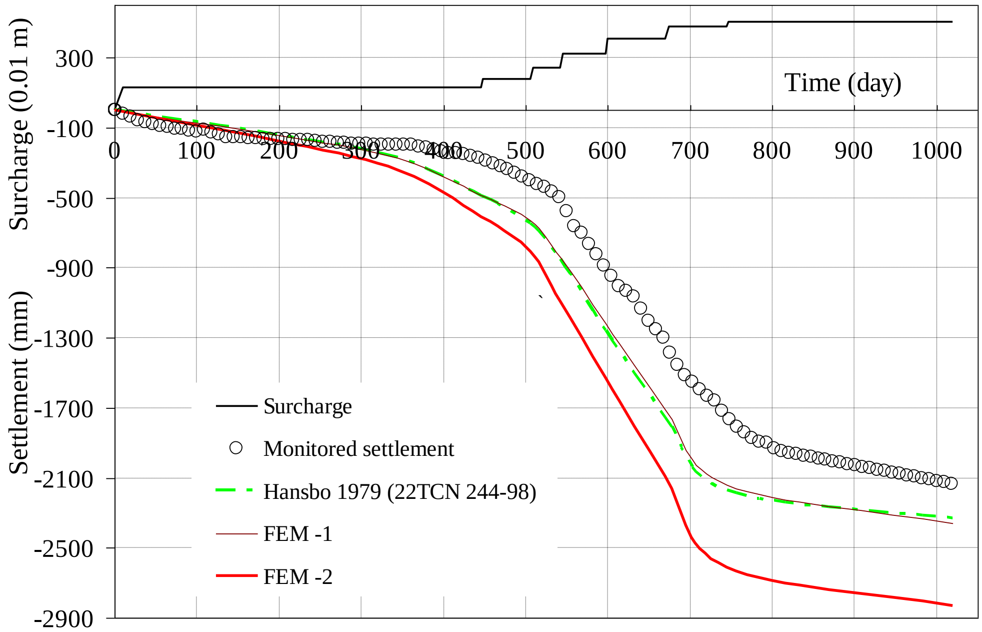

Figure 4. Simulation result for km 17 + 320 on the Saigon East-West Highway

Approach Embankment of Can Tho Bridge

Can Tho bridge on the National Highway No. 1A crosses the Hau river which is a branch of the Mekong river to connect Can Tho City and Vinh Long province with the total length of 15.35 km in which the main bridge is 2.72 km long and 12.63 km approach embankment. The Can Tho bridge project is about 160 km from the South of Ho Chi Minh City (Figure 5).

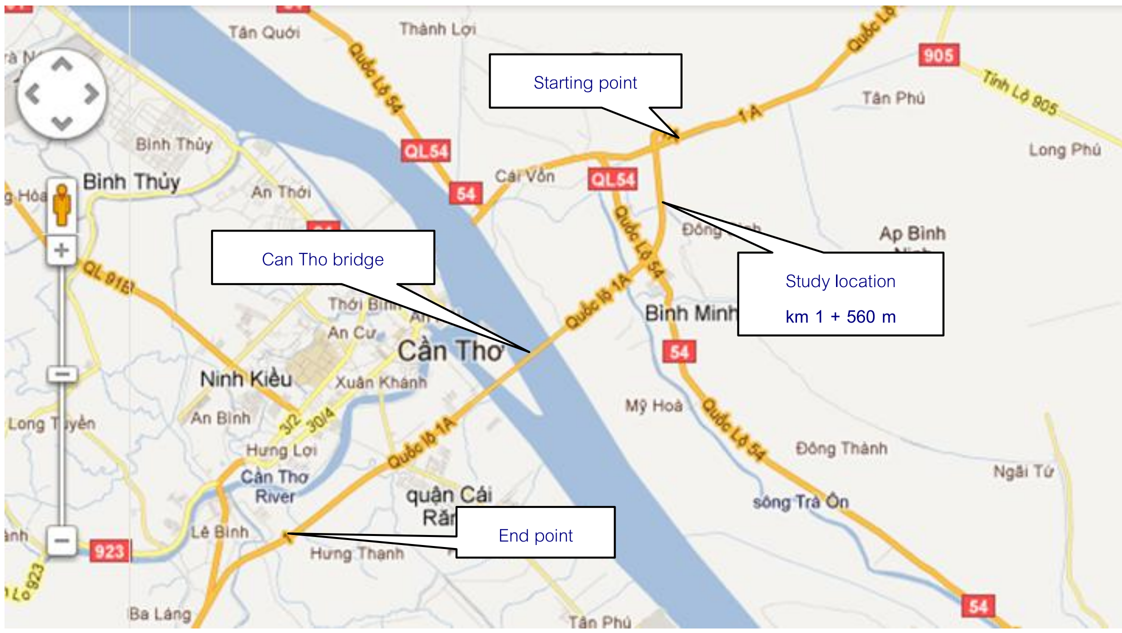

Figure 5. Study location (km 1 + 560) on the approach embankment of the Can Tho bridge project (Google map)

The cross-section of the approach embankment of the Can Tho bridge project is about 24 m wide designed for 4 lanes. The research section locates in Vinh Long province and at km 1 + 560. The soft ground of this section was improved using PVD. Along the 50 m subsoil profile, there are 2 layers: 28 m very soft clay layer at the top and > 23 m fine sand layer underneath. All soil properties of the study section are given in Table 2 and were provided by the contractors.

FD747 PVD made in Singapore with a PVD cross-section of (96.7 x 3.5 mm) was used for installation at 29 m length, 1.0 m spacing in triangular pattern. The initial discharge capacity of the PVD was 4451 m^3/year. Figure 6 shows arrangement of the study section, km 1 + 560, in detail.

Preloading was constructed in three major stages up to the final height of 2.56 m. The first fill was 0.5 m and maintained at 213 days. The second stage was 216 days long at the total fill height of 1.0 m, and the last one was 299 days. The field monitored settlement collected via the settlement plate S2 at the centerline of the embankment (Figure 6) is shown in Figure 7.

Similarly to the first case study, the simulated settlements were also analyzed using Hansbo's theory (1979) (22 TCN 244-98), FEM-1, and FEM-2. FEM meshes for the FEM-1 and FEM-2 models are showed in Figure 7a and 7b, respectively. The results are plotted in Figure 8.

The computed settlements agree well with the monitored settlement up to a fill height of 1.0 m in more than 400 days at an accumulated field settlement of 0.3 m. However, the simulated settlements were markedly diverging from the monitored settlement at the fill height of 2.56 m and the subsoil has experience a settlement of 0.5 or larger.

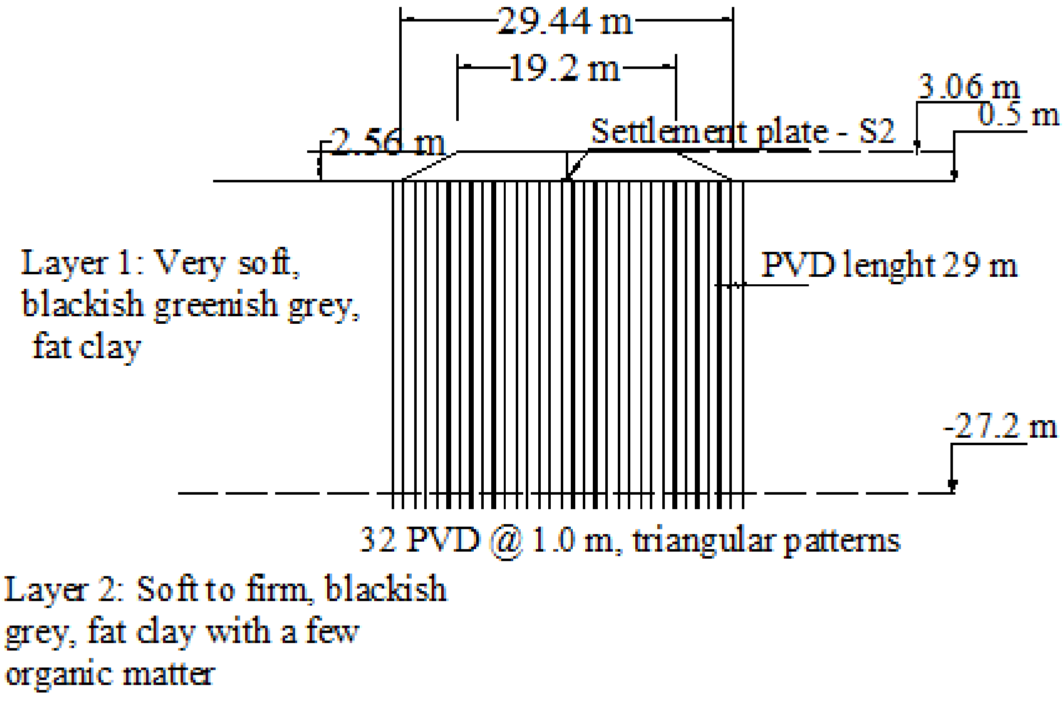

Figure 6. A typical cross-section of the highway embankment of the Can Tho Bridge

Table 2. Soil Properties at the Study Location km 1 + 560 on the Approach Embankment of the Can Tho Bridge

Soil type	Thick-ness m	γ kN/m³	E kN/m²	ν	φ (°)	c kN/m²	k_v m/day	k_h m/day
Very soft clay	27.7	16.5	1400	0.35	13.32	13.0	2.16E-04	2.59E-04
Fine loose sand	23.3	17.5	1980	0.3	15.49	20.3	1.45E-04	1.74E-04

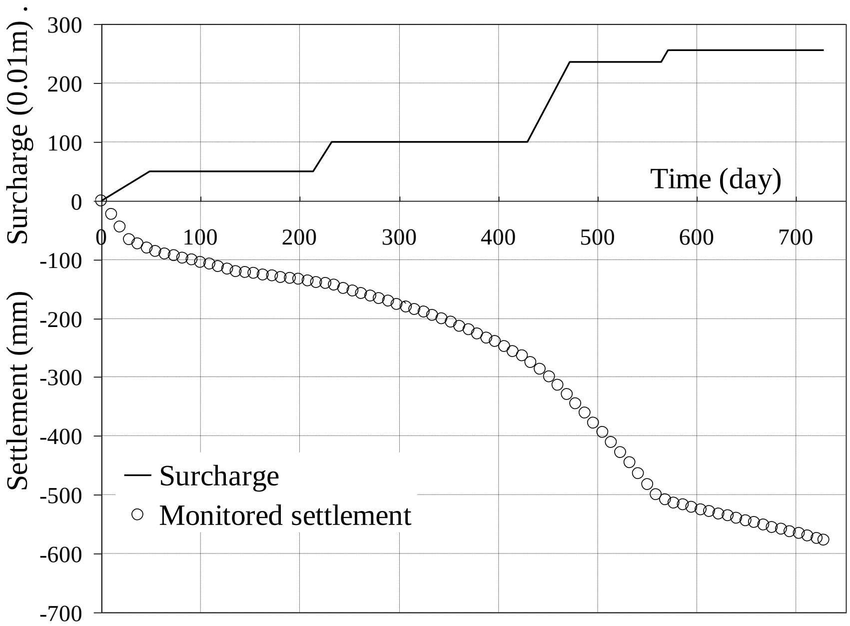

Figure 7. Field monitored settlement at km 1 +560 on the approach embankment of the Can Tho bridge project

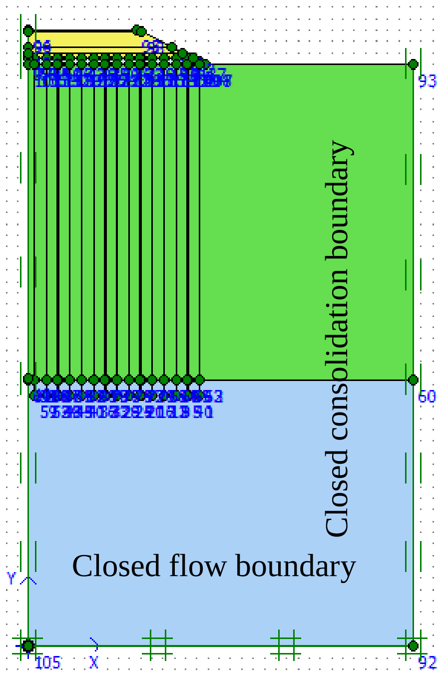

Figure 7a. A FEM-1 mesh for the initial conditions using the PLAXIS 2D software

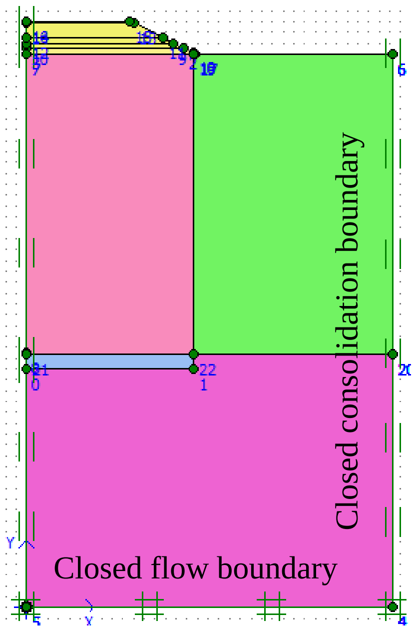

Figure 7b. A FEM-2 mesh for the initial conditions using the PLAXIS 2D software

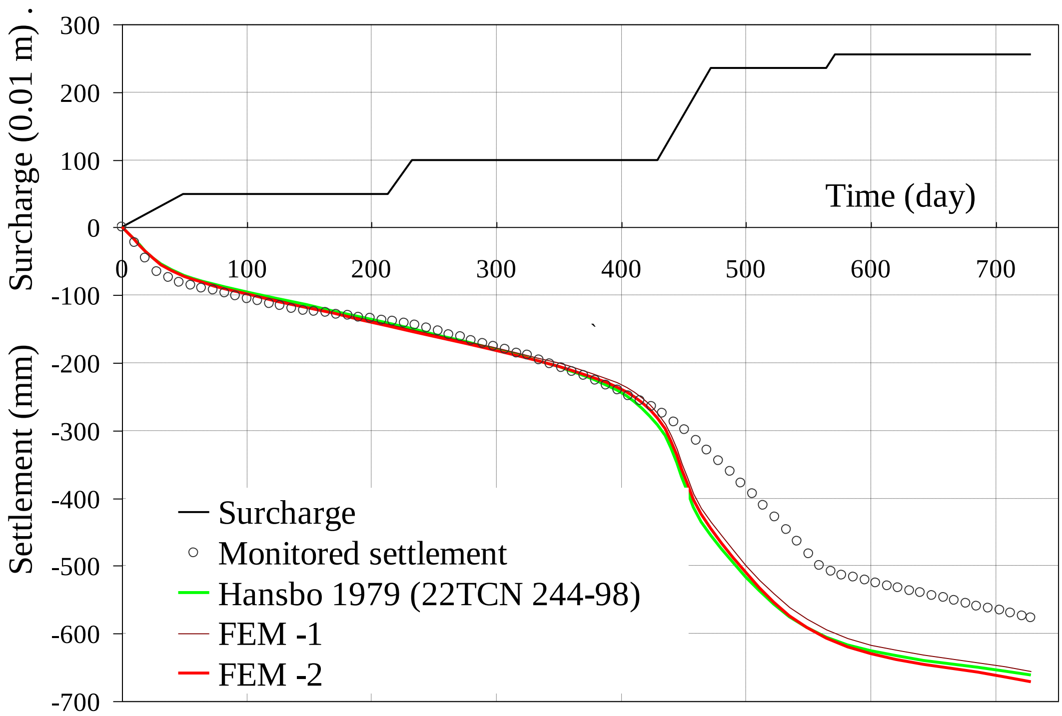

Figure 8. Simulated settlements to compare with the field monitored settlement at km 1 + 560 on the approach embankment of the Can Tho bridge project

Discussion

The case studies' results of the two projects indicate that the simulated settlements agree well with the monitored settlements when the field consolidation settlements were less than 0.3 m (Figure 4 & 8). Ha Hoan Hy & Tran Nguyen Hoang Hung (2011) also reported the similar results. The consolidation settlement took place at the first stage of a surcharge which is at low fill height (e.g., < 1.0 m), that is, small lateral pressure (e.g., < 150 kPa) affected insignificantly to the PVD (Rixner et al. 1986). Siltation may reduce the PVD discharge capacity by a factor of 2 (Bergado et al. 1996b), but q_w (e.g., ~ 300 m^3/year) is still high enough for its performance (e.g., > 150 m^3/year – Holtz et al. 1991). The consolidation settlement may be influenced by smear zone effects due to PVD installation process (Tran-Nguyen & Edil 2011, Tran-Nguyen 2010) but these simulations ignored these effects. It is noted that all simulations were assumed that all factors affected to PVD were neglected. In other words, assumption of ideal PVD is relevant for this stage (22 TCN 244-98 or Hansbo 1979).

The difference between the simulated settlements and field monitored settlements became more pronounced when the field consolidation settlement was excess 0.5 m. the biggest settlement discrepancy occurred right after the highest surcharge (e.g., 5.03 m at km 17 + 320 on the Saigon East-West highway, and 2.56 m at km 1 + 560 on the approach embankment of the Can Tho bridge). The percent of settlement difference up to 20% (FEM-1) and 57% (FEM-2). The similar behaviors were reported by Ha Hoan Hy (2011) and Ha Hoan Hy & Tran Nguyen Hoang Hung (2011).

At higher surcharges (e.g., 3 m), many factors influence the field performance of PVD, and settlement difference is more appreciable. Duration of surcharges was more than 600 days which is long enough for infiltration or siltation taking its effect (Chai et al. 2004). At a large field settlements (e.g., 2.2 m at km 17 + 320 on the Saigon East-West highway), PVD may be highly deformed due to large consolidation settlement (Tran-Nguyen et al. 2010, Tran-Nguyen 2010, Ali 1991). Friction between the filter sleeve of PVD and the soil mass surrounding the PVD may cause synchronous deformation of both the subsoil and PVD. Ha Hoan Hy & Tran Nguyen Hoang Hung (2011) reported that PVD discharge capacity reduced about 50% its initial discharge capacity when the field consolidation settlement is larger than 1.5 m for the soft ground in Ho Chi Minh City. Tran-Nguyen et al. (2010) also showed that PVD is severely deformed at large consolidation, and PVD discharge capacity reduces remarkably when the PVD has experienced a percent settlement of 30% or more. Lateral pressure becoming higher under higher surcharges (e.g., 3 m) causes reduction of PVD discharge capacity (e.g., lateral pressure >= 150 kPa – Rixner et al. 1986). This result indicates that the assumption that PVD performed ideally at large field consolidation settlement causes over-estimate settlement, especially wrong prediction of consolidation time.

The results show that simulations using FEM-1 (Indraratna & Redana 2000) and Hansbo (1979) (or 22 TCN 244-98) were close together whereas FEM-2 (Chai et al. 2001) was appreciably diverse with the FEM-1 and Hansbo (1979) at large consolidation settlement. The FEM-2 is only suitable to simulate for projects with small field consolidation settlement. At large field consolidation settlement, several factors affect the field performance of PVD, and equivalent hydraulic conductivity of PVD and subsoil suggested by Chai et al. (2001) may not be simple as Equation (7).

Conclusions

This study conducted back analysis utilizing the field settlement data of the two complete projects improving soft ground using PVD: the Saigon East-West highway project at km 17 + 320 and the approach embankment of the Can Tho bridge project at km 1 + 560. The three simulation models: Hansbo (1979) (or 22 TCN 244-98), FEM-1 (Indraratna & Redana 2000), and FEM-2 (Chai et al. 2001) were employed for this investigation. The Mohr-Coulomb model was employed to simulate the subsoil behavior. PVD was assumed to be ideal performance which ignores all factors that may affect the PVD. The results suggest the following conclusion:

- Assumption of ideal PVD works well when a field settlement is less than 0.3 m for the three simulation models for the two projects.

- When a field consolidation settlement is larger than 0.5 m, the predicted settlement is greater than the field monitored settlement. In order words, field performance of PVD needs to take into account for influenced factors such as PVD deformation, lateral pressure effect, smear zone effect, siltation effect, and so on.
- FEM-1 and Hansbo (1979) models are appropriate for PVD simulation.

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