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Back analyses of compressibility and flow parameters of PVD improved soft ground in Southern Vietnam

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ABSTRACT: Prefabricated vertical drains (PVD) have been used in Vietnam since the late 1990s years. However, evaluation of PVD performance remains a difficult problem to be solved due to the lack of a complete instrumentation. Recently, a construction project had been developed at Thi Vai Port, about 60 km southeast of Ho Chi Minh city. In this project, PVD with 1.2 m spacing was utilized to improve the soft clay underlying the storage yard of the port. Back analyses using graphical methods including Asaoka, log settlement versus time, settlement versus log time, and settlement rate versus inverse time plots were conducted to verify the primary and secondary settlements and to obtain the flow and compressibility parameters of the improved soft ground. The log settlement versus time plot introduced in this study has been proven to be very convenient for obtaining the immediate settlement and final consolidation settlement from the measured total settlement. Moreover, results from these analyses have confirmed that PVD had performed very well in terms of accelerating the primary consolidation of soft ground in Southern Vietnam. However, the rate of secondary settlement was also very high and such a substantial residual settlement should be considered in design practice of PVD-improved soft ground.

1 INTRODUCTION

Prefabricated vertical drains (PVD) have been used in Vietnam since last decade. The PVD performed well in most construction projects in terms of accelerating the primary consolidation. However, many of them have problems with the continuous residual settlement. One of the reasons causing these problems may be related to the design parameters and current design criteria without considering the secondary settlement (Long, 2005). In this paper, a procedure for estimating the primary consolidation settlement from measured total settlement is presented. Then, the compressibility and flow parameters including secondary consolidation of PVD improved soft ground at Thi Vai Port project in Southern Vietnam are investigated using graphical back analyses.

The soil profile and soil properties at the project site are presented in Fig. 1 and Fig. 2. The PVDs of 14 m length and 1.2 m spacing in triangle pattern were utilized for the treated area of 130 m by 296 m. The settlement monitoring was carried out in a period of about 460 days from June 2001 to September 2002. The measured settlements and surcharge filling versus time are presented in Fig. 3. The procedure and results of the back analyses are presented in following sections.

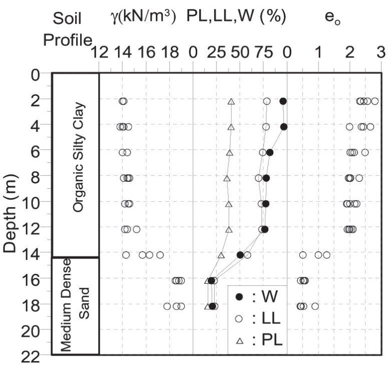

Figure 1. Soil profile and basic properties.

2 CONSOLIDATION AND COMPRESSIBILITY

2.1 *Consolidation with PVD*

Hansbo (1979) presented the solution for calculating the degree of horizontal consolidation, U_h, of soft ground improved by PVD as follows:

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

$$T_h = c_h t/D_e^2 \tag{2}$$

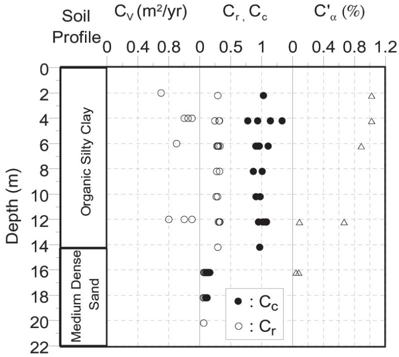

Figure 2. Flow and compression properties.

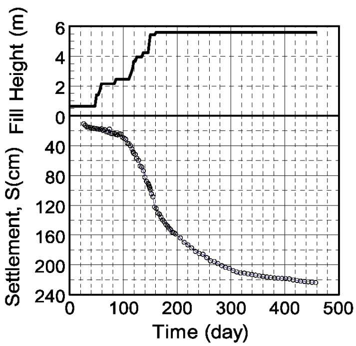

Figure 3. Measured settlement versus time.

$$F = F_n + F_s + F_r \quad (3)$$

$$F_n = \log_e (D_e/d_w) - 0.75 \quad (4)$$

$$F_s = (k_h/k_s - 1) \log_e (d_s/d_w) \quad (5)$$

$$F_r = \pi z(2L - z)\, k_h/q_w \quad (6)$$

where c_h is the coefficient of horizontal consolidation, D_e is the equivalent diameter of a unit PVD influence zone, d_w is the equivalent diameter of PVD, k_h is the horizontal permeability of the soft ground, k_s is the horizontal permeability of the smear zone, z is the distance from the drainage end of the drain, L is the length PVD of for one way drainage and is half of PVD length for drainage boundary at both ends of PVD, and q_w is the discharge capacity of the PVD.

Neglecting vertical consolidation, the primary consolidation settlement, S_{tc}, corresponding to degree of consolidation, U_t, can be calculated from the final primary consolidation, S_{fc}, as follows:

$$S_{tc} = S_{fc} \cdot U_t \quad (7)$$

2.2 *Back calculation of final primary consolidation settlement and immediate settlement*

Asaoka (1978) proposed a graphical method to predict the final settlement based on observation procedure.

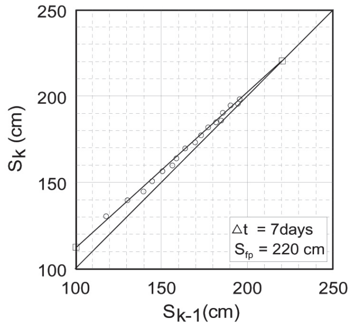

Figure 4. S_k versus S_{k-1} settlement plot.

From the monitored settlement data, the settlements S_k and S_{k-1} corresponding to time t_k and $t_{k-1} = t_k - \Delta t$ are read off and the relation $S_k \sim S_{k-1}$ is plotted. Then, the final primary settlement of S_{fp} of 220 mm can be obtained as shown in Figure 4. This value of S_{fp} consisted of final primary consolidation, S_{fc}, and immediate settlement, S_i, that can be obtained by following procedure.

From Eq. 7 and Eq. 1, it can be written:

$$S_{tc} / S_{fc} = 1 - \exp(-\alpha t) \quad (8)$$

$$\alpha = 8c_h/(D_e^2 F) \quad (9)$$

Equation (8) can be expressed in following form:

$$\log_e [S_{fc}/(S_{fc} - S_{tc})] = \alpha t \quad (10)$$

Substituting $S_{fc} = S_{fp} - S_i$ and $S_{tc} = S_t - S_i$ where S_t is the total settlement at time t, Eq. 10 can be rewritten in decimal logarithm as follows:

$$\log [S_{fc}/(S_{fp} - S_t)] = 0.434\alpha t \quad (11)$$

Equation 11 can be presented as a straight line through the origin but it is true only for the case of immediate loading as assumed in Eq. 8. However, the full surcharge can not be applied immediately in practice. Therefore, the measured settlements plotted in the relation of Eq. 11 can be fitted by a straight line intercepting the horizontal axis at $t = t_0$ as seen in Fig. 5. As such, following equations can derived for settlements from practical loadings as follows:

$$\log [S_{fc}/(S_{fp} - S_t)] = \alpha_1 (t - t_0) \quad (12)$$

$$\log(S_{fp} - S_t) = -\alpha_1 (t - t_0) + \log S_{fc} \quad (13)$$

$$\log S_{fc} = \alpha_1 (t_1 - t_0) \quad (14)$$

where $\alpha_1 = 0.434\alpha$.

Thus, the value of S_{fc} can be obtained from the plot of $\log(S_{fp} - S_t) \sim t$ plot as seen in Fig. 6 where the value of t_1 is the intercept of the straight line with the horizontal axis.

It is noted that the straight lines in Figs. 5 and 6 should be constructed through the points mainly dominated by primary consolidation (zone II in Fig. 5). Moreover, following iteration process is necessary because the value of S_{fc} in Eq. 12 is unknown:

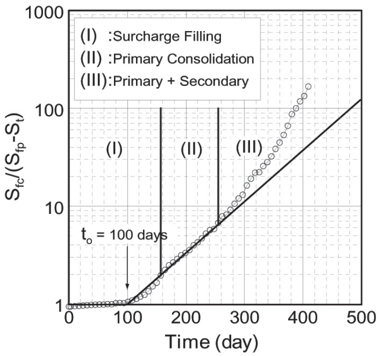

Figure 5. Log $[S_{fc}/(S_{fp} - S_t)]$ vs time plot.

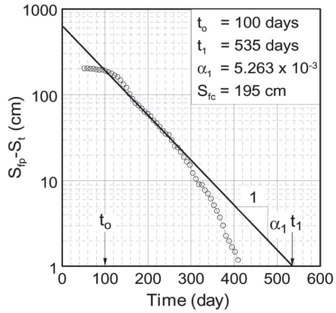

Figure 6. Log$(S_{fp} - S_t)$ versus time plot.

- Step 1: Assuming $S_{fc} = S_{fp}$, construct the log$[(S_{fc}/(S_{fp} - S_t)] \sim t$ plot for obtaining the values of t_0 and α_1 (Fig. 5).
- Step 2: Plotting the relation of log$(S_{fp} - S_t) \sim t$ to determine the values of t_0 and S_{fc} (Fig. 6).
- Repeat step 1 with S_{fc} obtained from step 2 until the difference between two iterations is negligible.

The results of this case study are as follows: α_1 = 0.0053, α = 0.0121, S_{fc} = 195 cm, and S_i = 25 cm.

Having S_{fc} and S_i, the average value of the compression coefficient, m_v, can be estimated as:

$$m_v = S_{fc}/[(H - S_i)\,\Delta\sigma'_{vf}] \tag{15}$$

where H is the thickness of the soft soil stratum, and $\Delta\sigma'_{vf}$ is the increase of final effective stress.

3 CALCULATION OF FLOW PARAMETERS

The c_h value can be calculated using Eq. (9) as:

$$c_h = 0.125\,\alpha D_e^2 F \tag{16}$$

Assuming the compressibility coefficient in vertical direction, m_v, is equal to that in horizontal direction, the following expression can be written:

$$k_h = \gamma_w m_v c_h \tag{17}$$

Substituting for k_h from Eq. 17, for F using Eqs. 3, 4, 5, and 6, into Eq. 16, the following equation can be derived:

$$c_h = C_1(F_n + F_s)/(1 - C_1C_2/q_w) \tag{18}$$

where:

$$C_1 = 0.125\,\alpha D_e^2 F \tag{19}$$

$$C_2 = \pi z\,(2L - z)\gamma_w\, m_v \tag{20}$$

Equation 18 consists of four unknowns: k_s, d_s, q_w and c_h. Thus, the back-calculated values of c_h will be dependent on the assumed values of the other three unknowns. By assuming the diameter of smear zone d_s is twice of the equivalent diameter of the mandrel, d_m, as suggested by Hansbo (1987), the relationship between c_h and q_w can be obtained for different values of $R_s = k_h/k_s$. For PVD section of 0.003 m × 0.100 m (Nylex Megawick type) and mandrel section of 0.06 m × 0.12 m, the calculated results are presented in Fig. 7 which indicated that the c_h values become little affected by the value of discharge capacity when q_w is greater than 50 m^3/year. With the assumed values of d_s/d_m = 2, k_h/k_s of 2 and 5, the corresponding calculated c_h values are about 4 m^2/year and 6 m^2/year, respectively, which is about 4 to 6 times greater than the c_v value obtained from conventional oedometer tests.

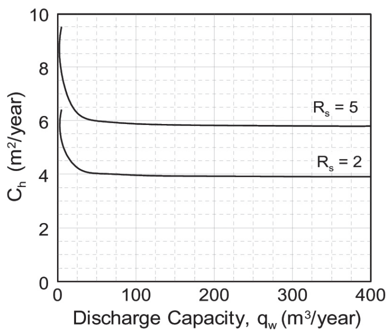

Figure 7. Back-calculated c_h versus q_w relationship.

4 SECONDARY SETTLEMENT

The secondary settlement at time t, S_s, can be estimated from the secondary compression ratio, C'_α, the soft soil thickness, H, and the time at the end of primary consolidation, t_p, as follows:

$$S_s = C'_\alpha H \log(t/t_p) \tag{21}$$

From Eq. 21, following equation can be derived:

$$\Delta S_s/\Delta t = C'_\alpha H/t \tag{22}$$

Thus, the $C'_\alpha H$ value can be obtained as the slope of the straight line from the settlement rate $(\Delta S_s/\Delta t)$ versus inverse time $(1/t)$ plot as presented in Fig. 8.

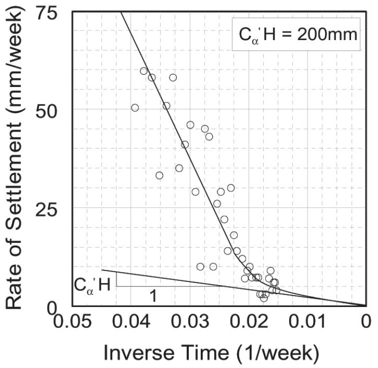

Figure 8. Rate of settlement versus inverse time.

From $C'_\alpha H$ = 200 mm as obtained in Fig. 8, with H = 14 m, the back-calculated value of C'_α is 1.43%.

Further insight into the settlement characteristics can be seen in Fig. 9 with the secondary consolidation line constructed from the back-calculated values of ($C'_\alpha H$) and S_{fp}. From this figure, the estimated secondary settlement in 20 years is about 28 cm with the rate of greater than 6 cm/yr for the first 3 years.

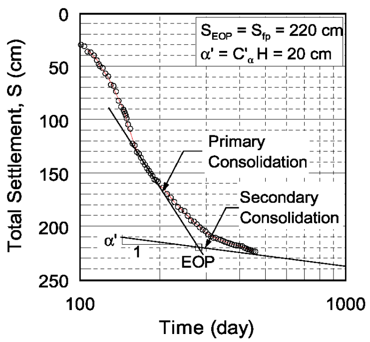

Figure 9. Total settlement versus time.

5 CONCLUSIONS

A procedure for estimating the immediate settlement and final primary consolidation settlement from observed settlements has been introduced in this paper. Back analyses of flow and compressibility parameters including secondary consolidation have been conducted. The back-calculated value of c_h is about 4 to 6 times of the average c_v value obtained from conventional oedometer test. The C'_α value from back calculation is about 1.5 times of that from laboratory test. The substantial secondary settlement suggested that the secondary settlement should be included in designing PVD improved soft ground.

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