

# 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.

## 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:

$$U_h = 1 - \exp(-8T_h/F) \quad (1)$$

$$T_h = c_{ht} / D_e^2 \quad (2)$$

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

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

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

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

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.

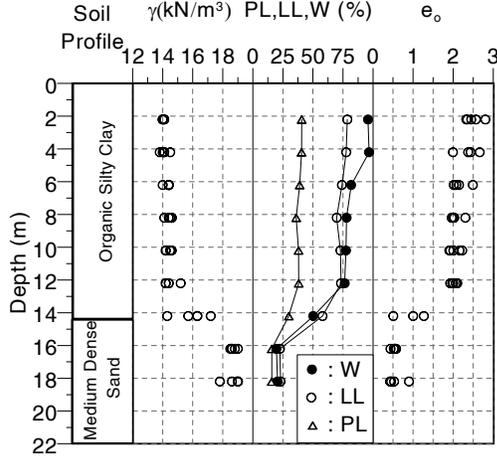


Figure 1. Soil profile and basic properties

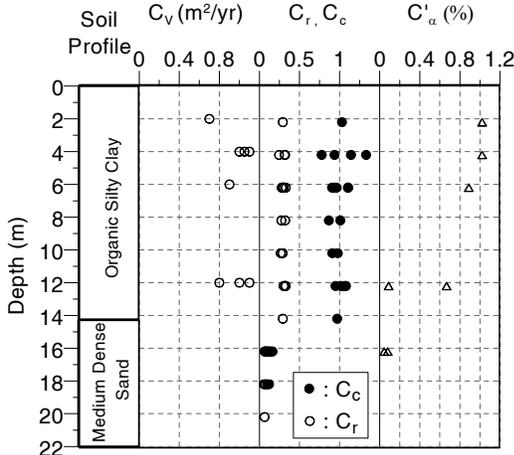


Figure 2. Flow and compression properties

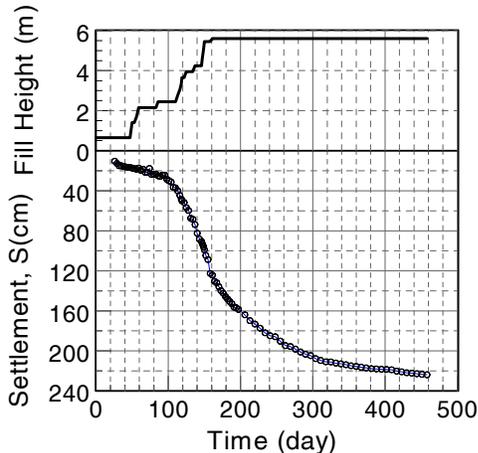


Figure 3: Measured settlement versus time

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:

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

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

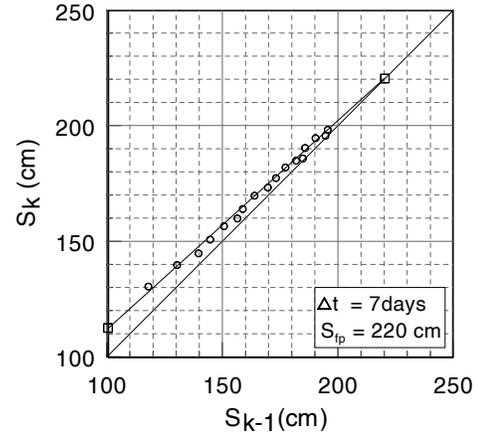


Figure 4.  $S_k$  versus  $S_{k-1}$  settlement plot

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

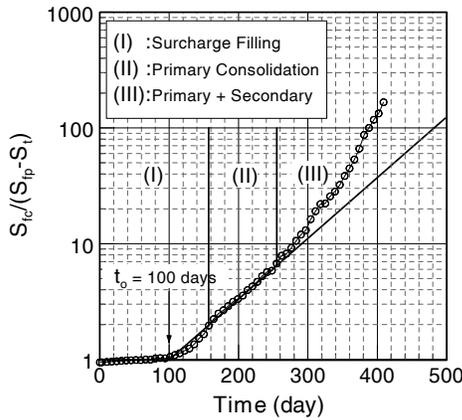


Figure 5.  $\log[S_{fc} / (S_{fp} - S_t)]$  vs time plot

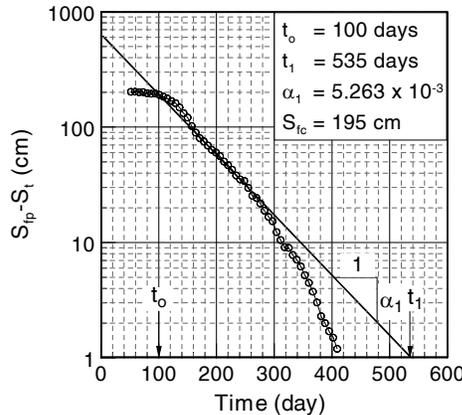


Figure 6.  $\log(S_{fp} - S_t)$  versus time plot

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:

- 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  $\alpha_1$  (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:  $\alpha_1 = 0.0053$ ,  $\alpha = 0.0121$ ,  $S_{fc} = 195$  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:

$$m_v = S_{fc} / [(H - S_i) \Delta \sigma_{vf}'] \quad (15)$$

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:

$$c_h = 0.125 \alpha D_e^2 F \quad (16)$$

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

$$k_h = \gamma_w m_v c_h \quad (17)$$

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:

$$c_h = C_1 (F_n + F_s) / (1 - C_1 C_2 / q_w) \quad (18)$$

where:

$$C_1 = 0.125 \alpha D_e^2 \quad (19)$$

$$C_2 = \pi z (2L - z) \gamma_w m_v \quad (20)$$

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 x 0.100 m (Nylex Megawick type) and mandrel section of 0.06 m x 0.12 m, the calculated results are presented in Fig. 7 which indicated that the  $c_h$  values become little'e affected by the value of discharge capacity when  $q_w$  is greater than 50

$\text{m}^3/\text{year}$ . 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  $4 \text{ m}^2/\text{year}$  and  $6 \text{ m}^2/\text{year}$ , respectively, which is about 4 to 6 times greater than the  $c_v$  value obtained from conventional oedometer tests.

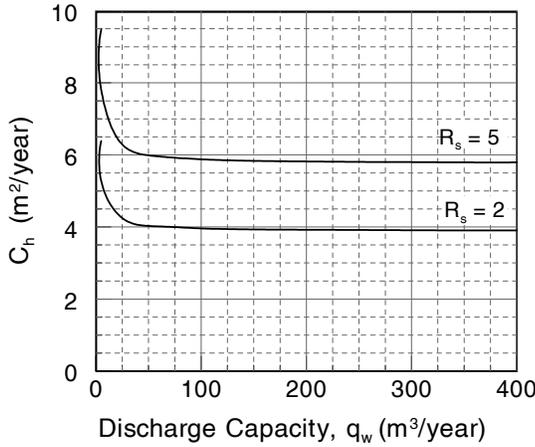


Figure 7. Back-calculated  $c_h$  versus  $q_w$  relationship

#### 4 SECONDARY SETTLEMENT

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

$$S_s = C_\alpha' H \log(t/t_p) \quad (21)$$

From Eq. 21, following equation can be derived:

$$\Delta S_s / \Delta t = C_\alpha' H / t \quad (22)$$

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.

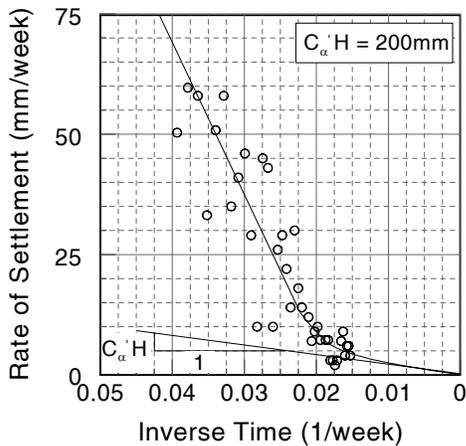


Figure 8. Rate of settlement versus inverse time

From  $C_\alpha' H = 200 \text{ mm}$  as obtained in Fig. 8, with  $H = 14\text{m}$ , the back-calculated value of  $C_\alpha'$  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.

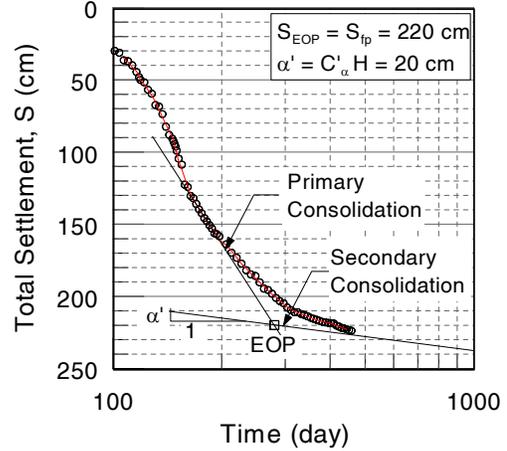


Figure 9. Total settlement versus time

#### 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  $C_\alpha'$  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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