Effect of Vacuum Pressure Distribution on Settlement Analysis Results for An Improved Thick Soft Clay Deposit at Sai Gon-Hiep Phuoc Terminal Port, South of Vietnam

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ABSTRACT: In the recent years ground improvement with preloading, PVD and vacuum pressure has become commonly used for many projects in Southern Vietnam, including that of Sai Gon-Hiep Phuoc (SGHP) terminal port. At this project site a very soft to soft clay layer was improved by a combination of three techniques as mentioned above. As the clay deposit is very thick, extending from the surface to the depth of 35m, the effect of vacuum pressure along the PVD and the immediately surrounding soil is of particular interest in term of its influence on the settlement analysis among other parameters, commonly considered in settlement analysis, such as soil properties, smear zone, PVD spacing etc. In this study, the effect of ratio between vacuum pressure at the bottom and the top of the drain (k_p) on the settlement analysis results, was investigated using a Fortran code. It was found that k_p varied from 0.85 to1.0 and its value could affect the matching of the calculated settlement curve with monitoring data if not properly chosen. In addition, the smear effect with RS equal to 3.0 and a PVD spacing of 1.0 m were found as optimal values for settlement analysis at the SGHP site.

KEYWORDS: Sai Gon-Hiep Phuoc port terminal, Soft clay, Ground improvement, Vacuum pressure, Settlement analysis

1. INTRODUCTION

Sai Gon-Hiep Phuoc (SGHP) Port Terminal is located in the Sai Gon–Dong Nai river delta (Figure 1), near to Soai Rap river. The project site covers an area of 39.12 hectare. SGHP port terminal will be constructed to replace the old SG Terminal in the centre of HCM city. The soft soil layers at the study site are distributed approximately 35-m deep and ground improvement by vacuum consolidation was performed to ensure stabilization of a container yard with a design 6.0-kPa service loading. The main objective of this research is to investigate the effects of distribution of vacuum pressure along the vertical drain installed in the very thick soft clay deposit on the settlement.

Figure 1 Site Location

2. CALCULATION OF TIME-DEPENDENT PRIMARY CONSOLIDATION SETTLEMENT

A FORTRAN code (Giao, 2013) was employed to perform the settlement analysis, whose main steps are briefly explained in the folowing.

2.1 Calculation of Embankment Loading

Calculation of the contribution of the embankment loading (surcharge) to the increase in total vertical stress is based on Boussinesq's equation for a point loading:

$$d\sigma_{v(i,j)} = \frac{q}{z_{i,j}^2}\,\frac{3}{2\pi}\,\frac{1}{[(x_{i,j}/z_{i,j})^2+1]^{5/2}} \qquad (1)$$

Where: $d\sigma_{v(i,j)}$ is the stress increase induced by the surcharge at the calculated point (i,j); q is the load intensity; $x_{i,j}$, $z_{i,j}$ are the horizontal and vertical coordinates of the calculated point (i,j). Index i refers to sub-layer numbering in vertical direction (vertical), while index j refers to the calculated point location (horizontal).

2.2 Main Types of Settlement

The total settlement of the soft clay under loading consists of the immediate settlement (S_i), the consolidation settlement (S_c) and the secondary settlement (S_s). The first and second settlements make up the so-called primary settlement (S_p). The immediate settlement or initial settlement occurs before consolidation due to lateral strains or lateral movement due to finite dimension of the loading and vertical drain installation:

$$S_p = S_i + S_c = S_i + \xi S_p \Rightarrow S_i = (1-\xi)S_p \qquad (2)$$

In the equation (2) ξ is defined as the ratio between the consolidation settlement (Sc) and the primary settlement (Sp) and it is practically considered to vary from 0.7 to 0.9 depending on the ratio between the loading width and thickness of the clay layer, OCR of soft clay and construction sequence.

2.3 Final Consolidation Settlement

The final consolidation settlement is calculated as follows:

$$dS_{C(i,j)} = h_i.[RR_{(i,j)}.\log\frac{\sigma'_{vf(i,j)}}{\sigma'_{v0(i,j)}}] \quad (3)$$

$$dS_{C(i,j)} = h_i.[RR_{(i,j)}.\log\frac{\sigma'_{p(i,j)}}{\sigma'_{v0(i,j)}} + CR_{(i,j)}.\log\frac{\sigma'_{vf(i,j)}}{\sigma'_{p(i,j)}}] \quad (4)$$

$\sigma'_{vf(i,j)} = \sigma'_{vo(i,j)} + \Delta\sigma_{v(i,j)} + \Delta U_{(i,j)}$ For surcharge loading.

$\sigma'_{vf(i,j)} = \sigma'_{vo(i,j)} + \Delta\sigma_{v(i,j)} + \Delta U_{(i,j)} + P_{vac}$ For surcharge loading combined with vacuum pressure.

Where: $\sigma'_{p(i,j)}$ is the preconsolidation pressure; $\sigma'_{vo(i,j)}$ is the effective stress; $\Delta\sigma_{v(i,j)}$ is the increase in total stress due to surcharge loading; $\Delta U_{(i,j)}$ is the dissipation of pore pressure at the point(i,j); $CR_{(i,j)}$ is the compression ratio; $RR_{(i,j)}$ is the recompression ratio; P_{vac} is the vacuum pressure.

Eq. 3 is used when the increased effective stress is still less than the preconsolidation pressure of the improved soil, while Eq. 4 is used the increased effective stress becomes more than the preconsolidation pressure of the soil.

In PVDVAC program (Giao, 2013), the improved clay layer is divided into sub-layers, and the total primary consolidation settlement is a sum of contributions from each individual sub-layer:

$$S_C = \sum_{i=1}^{n} dS_{C(i,j)} \quad (5)$$

Where: S_C is the total settlement of the analyzed clay layer and $dS_{C(i,j)}$ is the settlement of the sub-layer i at location j.

2.4 Time-Dependent Consolidation Settlement

Time-dependent consolidation is the most important component of settlement to be calculated for a soft clay foundation improved by vertical drains.

Rate of vertical consolidation

The degree of vertical consolidation can be calculated as follows:

$$Uv_{i,t} = 1 - u_t / u_0 \quad (6a)$$

$$u_t = \sum_{m=0}^{\infty}\left[\frac{2.u_o}{M}\sin\left(\frac{Mz_i}{H}\right).\exp^{-M^2T_v}\right] \quad (6b)$$

$M = \pi(2m+1)/2$

$T_v = c_v t/H^2$

Where: m is an integer number; $U_{vi,t}$ is the degree of consolidation at depth i, time t; ut is the pore pressure at depth i, time t; u_0 is the initial pore pressure just after loading; c_v is the vertical consolidation coefficient; T_v is the time factor corresponding to depth i, time t; H is the drainage path.

Rate of horizontal consolidation

The degree of consolidation in the horizontal direction can be calculated based on the Hansbo's (1979) solution as follows:

$$U_h(t) = 1-\exp(-8T_{h,i}/F) \quad (6c)$$

$$T_{h,i} = c_{h,i}.t/D_e^2 \quad (6d)$$

$F = Fn + Fs + Fr$

$Fn = \ln(De/d_w) - 0.75$

$Fs = [k_h/k_s-1]\ln(d_s/d_w)$

$Fr = \pi z_i(L-z_i)k_h/q_w$

Where: $T_{h,i}$ is the time factor corresponding to depth i, time t; c_h is the horizontal consolidation coefficient ; D is spacing of vertical drain installation; De is the effective diameter of a drain. De = 1.05D and 1.13D for a triangular or rectangular pattern, respectively; d_w is the equivalent diameter of the drain; k_h is the horizontal permeability of the undisturbed soil; k_s is the horizontal permeability of the soil in the smear zone; L is the length of the drain; d_m is the equivalent diameter of the mandrel and d_s is the diameter of the disturbed zone (d_s = 2 to 3 d_m).

2.5 Degree of Consolidation

The degree of consolidation of the sub-layer i is calculated by the following equation:

$$U_{i,t} = 1 - (1 - U_{h,i})(1 - U_{v,i}) \quad (7)$$

For the layers beyond the length of drains Uh is considered zero. By combining Eqs. (5) and (7), the time-dependent primary consolidation settlement of a clay improved by VD can be calculated as follows:

$$S_{i,t} = U_{i,t}.Sc \quad (8)$$

However, due to the three-dimensional effect, the increase in the vertical effective stress is just a part besides the increase in the horizontal effective stress. Therefore, the equation below will be better used, taking into account the immediate settlement:

$$S_{i,t} = \xi U_{i,t}Sc \quad (9)$$

3. SETTLEMENT ANALYSIS

3.1 Study site location

SGHP project is a one of the container terminal projects in the Hiep Phuoc Port Group, which located at the southern gateway of the Ho Chi Minh City. The reclamation works of this project have been started since 2009 and divided into many packages corresponding to the service loads. Ground improvement with surcharge, PVD and vacuum pressure was applied to ensure the stability of container yard zone. In this reclaimed region, a full scale of embankment (phase A5) was selected for research (see Figure 3).

3.2 Soil characterization and Geotechnical properties

Soil characterization was done and plotted in Figure 2 that shows the geotechnical profile of the average geotechnical properties with depth up to 50 m deep, which are also summarized in Table 1 & Table 2. There are three main soil layers, i.e.: (1) the thick very soft to soft clay layer (from the surface to about 35 m) is divided into two sub layers, and namely, the very soft clay denoted as layer 1a (from the ground surface to the depth of 17 m) and the soft clay denoted as layer 1b (from 17 to 35 m deep).The very soft to soft clay is a grayish black and organic soft soil with a low unit weight; (2) The second layer of sandy soil underlies the soft clay and is located from 35 to 40 m deep. It is identified as grey yellowish, grey brown, loose state to medium dense sand; (3) The bluish grey, yellowish grey stiff to hard clay underlying the sand layer (located from 40 m downwards). Consolidation parameters of soil layers were determined by laboratory and field tests, and namely, the coefficient of vertical consolidation (C_v) values were estimated from the oedometer tests using Casagrande's method, while the coefficients of horizontal consolidation (C_h) values were derived from piezocone tests, respectively. The changes with depth of these properties, including compression index (C_c), swelling index (C_s), vertical coefficient of consolidation (c_v) and horizontal coefficient of consolidation (c_h) are shown in Figure 2 and Table 2.

3.3 Embankment Construction Sequence and monitoring work

General plan of reclamation brakeage at SGHP project is shown in Figure 3 with 12 phases (including B1 to B6 and A1 to A6). The study site is located in the A5 phase area with full scale embankment test as seen in Figure 3. Four settlement points were placed on boundary of zone (SP21, SP22, SP24, and SP25) and 01 point was placed at the center of embankment zone (SP23). In addition, 01 piezometer (P05), 01 extensometer (E05) and 01 observation well (OB05) were installed at center of study zone. The section of the instrumentation is sketched in Figure 4.

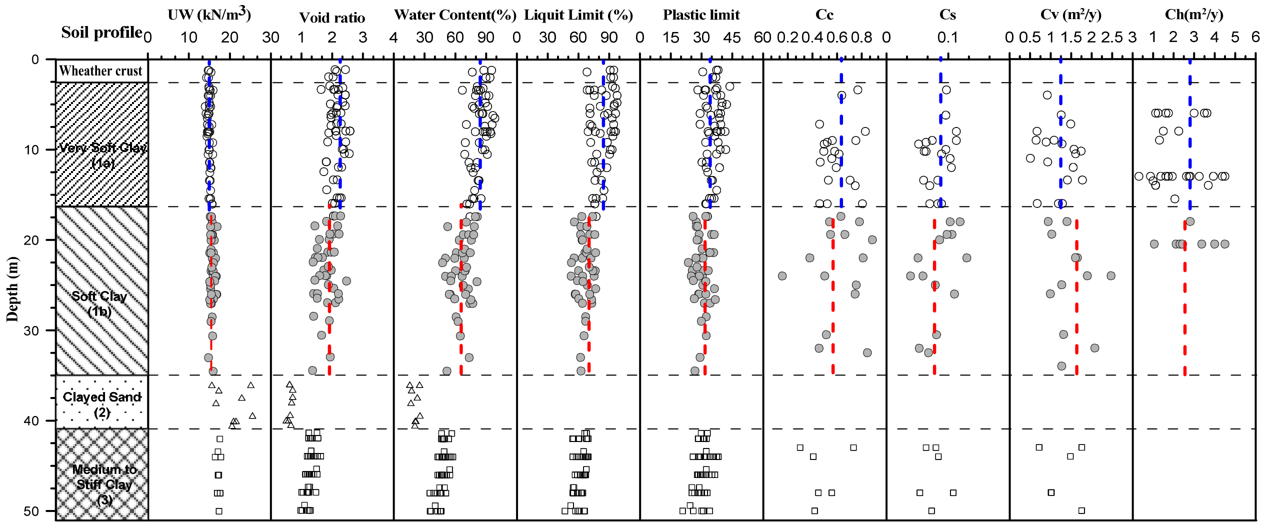


Figure 2 Geotechnical profile of the subsoil at the SGHP site

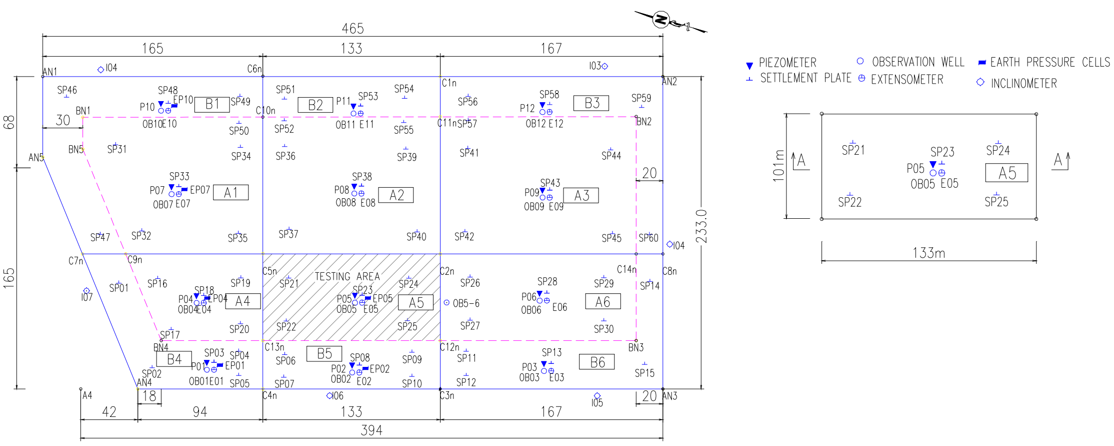


Figure 3 Location of testing embankment site and monitoring setup

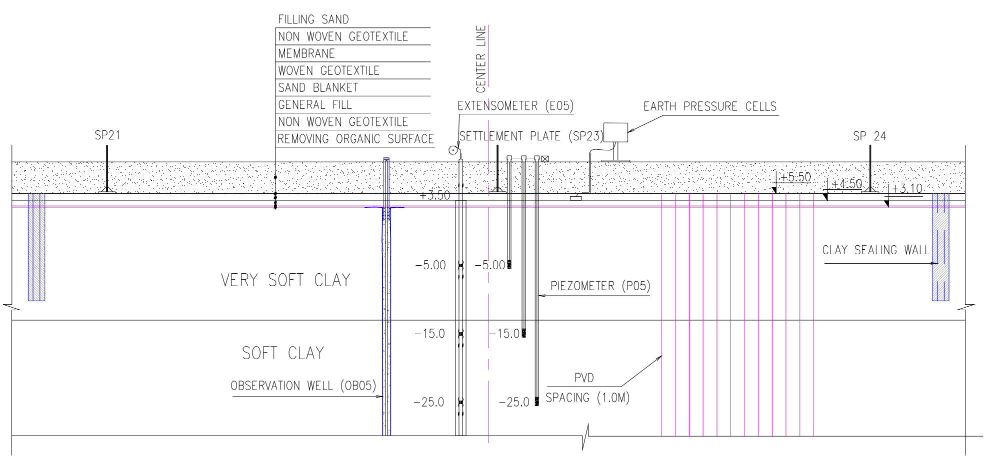


Figure 4 Section A-A at Phase A5 area.

The sequence of embankment construction and installation of monitoring instruments can be summarized as follows: (i) Removing organic layer and placement of 1.3m thick sand fill; (ii) Filling of a 1.0 m thick sand blanket; (iii) Installation of vertical drains to a depth of about 34 m; (iv) Vacuum pumping system setup; (v) Installation of settlement and pore pressure monitoring instruments (surface settlement plates, settlement gauges, extensometers, piezometers); (vi) Vacuum pumping; (vii) Stages of embankment loading and maintenance at 5.4 m height, respectively.

Table 1 Basic geotechnical properties at SGHP site

Layer Name	Unit weight (kN/m^3)	Void ratio	Water content (%)	Liquid limit (%)	Plastic limit
1a	15.1	2.167	81.9	81.0	35.0
1b	15.8	1.751	65.1	64.7	30.3
2	19.9	0.619	20.7	16.4	10.3
3	18.8	0.929	33.9	62.7	18.6

Table 2 Basic geotechnical properties at SGHP site (continue)

Layer Name	C_c	C_s	c_v (m^2/year)	c_h (m^2/year)	σ'_p (Kg/cm^2)
1a	0.63	0.085	1.25	2.6	1.08σ'_{vo}
1b	0.565	0.070	1.66	2.4	1.00σ'_{vo}

3.4 Input data for settlement analysis

Construction stages to be simulated are as follows:

- Stage 01: PVD installation and sand blanket construction.
- Stage 02: Vacuum pumping testing.
- Stage 03: Vacuum combined surcharge.
- Stage 04: Surcharge final and consolidation time.

The ξ coefficient (see equation 2) equal to 0.85 was chosen. The secondary compression was not calculated for the period of settlement analysis in this study. The input parameters used in settlement analyses are shown in Table 3.

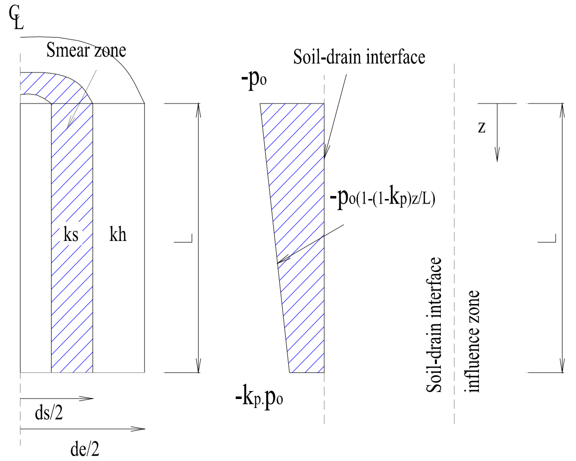
The horizontal and vertical consolidation coefficients of the soil layers were assumed to be decreased during consolidation when the increased effective stress becomes higher than the preconsolidation pressure. This is an improvement to Hansbo's solution, taking into account non-linearity of consolidation parameters. For examples, the vertical consolidation coefficient, c_v, of the very soft clay (Table 3) were 4.0 m^2/year and 1.2 m^2/year before and after preconsolidation, respectively. The horizontal consolidation coefficient, c_h, of all three soil layers were 19.4 m^2/year before preconsolidation and around 2.5 m^2/ year after preconsolidation.

The designed vacuum pressure (70 kPa) was used for settlement analysis and distribution of negative pore pressure due to vacuum pumping followed Indraratna et al. (2004) as seen in Figure 5, taking into account the ratio between vacuum pressure at the bottom and the top of the drain (k_p).

3.5 Results and discussion

Three main analyses were carried out as follows:

First Analysis: as seen in Figure 6, the measured settlement data show a large consolidation settlement up to 4.3 m after 1.2 years of construction. The calculation was done with the initial input data shown in Table 4, in which the ratio (RS) varied from 2.0 to 3.0, 5.0, while the ratio between vacuum pressure at the bottom and the top of the drain k_p =1.0 for all vacuum pumping construction stages. The specific discharge of vertical drain at a unit hydraulic gradient (Q_w) was selected based on ASTM D-4716 with Q_w = 2000 m^3/year and the spacing of the VD installation was 1.0 m. The analysis results showed that the calculated settlement with Rs = 2.0 matched quite well with the observed settlement for from stage 01 to the early stage 02, but not after that, as seen in Figure 6 , to get a better fit one needs to consider the effect of vacuum loading distribution with depth.



Note: p_o is vacuum pressure along PVD

Figure 5 Vacuum pressure distribution along the drain length after Indraratna et al. (2004)

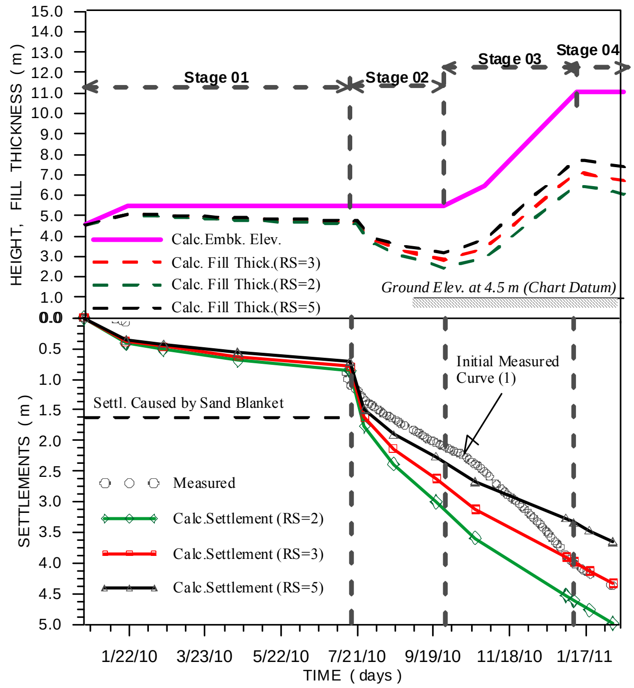


Figure 6 Analysis 1- Smear Zone effect

Second Analysis: This mainly aimed at stimulating the settlement in the stages 02 and 03. The calculation was conducted with Rs = 3.0, Q_w = 2000 m^3/year and d =1.0 m. The k_p varied from 0.8 to 0.9 for individual construction stage. Results shown in Figure 7 indicated that the suitable values of k_p are 0.8, 0.85 to 0.9 for the vacuum pumping testing, vacuum with surcharge and consolidation stages, respectively.

Third Analysis: was carried out with the soil parameters shown in Table 4. The PVD parameters were chosen as follows: RS=3.0, Q_w = 2000 m^3/year, D =1.0m. The settlement curves were calculated with k_p =0.85 for pumping testing stage, k_p = 0.95 for stage 01 and k_p =1.0 for consolidation state gave the best fit to the measurements (see results of analysis 3 in Figure 8).

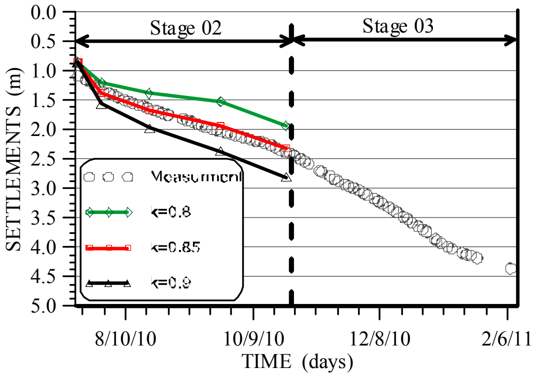
Table 3 Initial Parameters for Settlement Analysis at Hiep Phuoc Location

Soil Type	**Depth** (m)	W (%)	U_W (t/m^3)	c_{v1} (m^2/y)	c_{v2} (m^2/y)	c_{h1} (m^2/y)	c_{h2} (m^2/y)	OCR	CR	RR
Very Soft Clay (CL)	5.0	82	1.51	4.00	1.25	19.4	2.6	1.08	0.2	0.027
	17.0	65	1.51	6.07	1.66	19.4	2.6	1.08	0.2	0.027
Soft and medium Clay (CL)	35.0	65	1.58	6.07	1.66	19.4	2.4	1.00	0.205	0.027

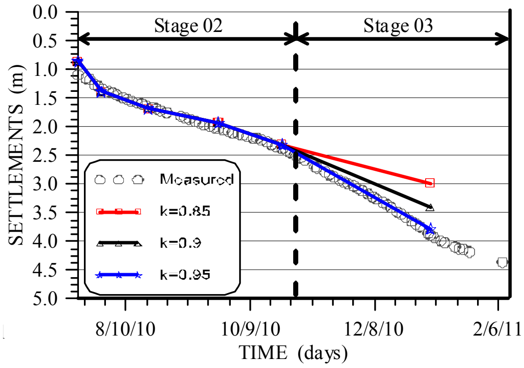
Note:
c_{v1},c_{v2}: Coefficient of vertical consolidation in OC,NC stage.
c_{h1},c_{h2}: Coefficient of horizontal consolidation in OC,NC stage.
k_h = 0.12 m/year was used for both sub layers.

Table 4 Summary of Settlement Analysis at Hiep Phuoc Location

Analysis	**Scopes**	**Parameters Used**	**Stages**	**Remarks**
ANALYSIS 01	Effects of the smear zone	Initial Soil parameters		
(Figure 6)		D = 1 m		
		Q_w = 2000 m^3/year		
		RS = 2.0	Stage 02	Underestimation
			Stage 03	Underestimation
			Stage 04	Underestimation
		RS = 3.0	Stage 02	Underestimation
			Stage 03	Poor matching
			Stage 04	Well matching
		RS = 5.0	Stage 02	Poor matching
			Stage 03	Underestimation
			Stage 04	Underestimation
ANALYSIS 02 (Figure 7)	Effects of negative pore pressure distribution versus depth	Initial Soil parameters D =1 m, Q_w = 2000 m^3/year RS=3		
		K = 0.80	Stage 02	Underestimation
		K = 0.85	Stage 02	Well matching
		K = 0.90	Stage 02	Underestimation
		K = 0.85	Stage 03	(Using K=0.85 for stage 02) Poor matching
		K = 0.90	Stage 03	(Using K= 0.85 for stage 02) Quite well matching
		K = 0.95	Stage 03	(Using K=0.85 for stage 02) Well matching
ANALYSIS 03 (Figure 8)		Initial Soil parameters, D =1m, Q_w = 2000 m^3/year, RS=3		
		K = 0.85	Stage 02	Good prediction
		K = 0.95	Stage 03	Good prediction
		K = 1.00	Stage 04	Good prediction



Analysis 2 - Effect of negative pore pressure distribution verus depth in stage 02



Analysis 2 - Effect of negative pore pressure distribution verus depth in stage 03

Figure 7 Analysis 2- Effects of negative pore pressure distribution versus depth

Note: *During the PVD installation and sand blanket construction stage, the collected monitoring data are discontinuous and diffuse.*

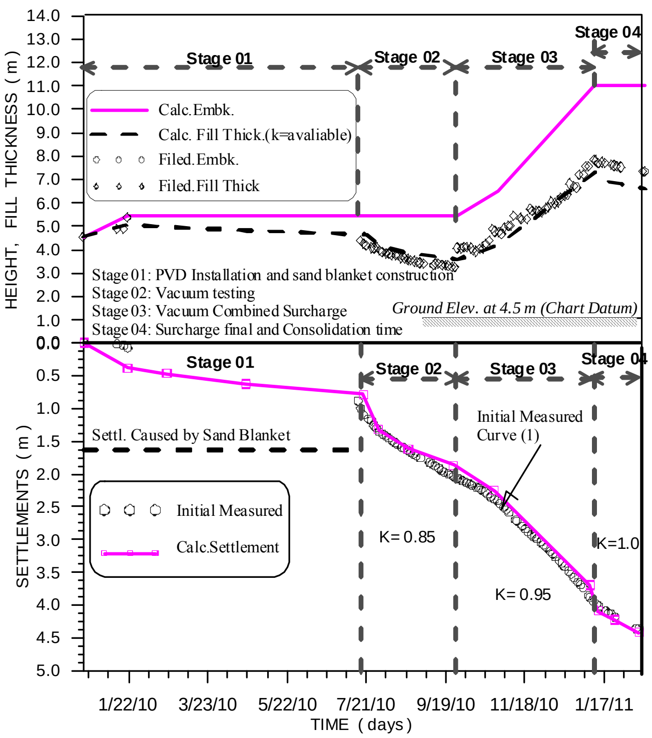


Figure 8 Analysis 3- Settlement analysis (Effects of negative pore pressure distribution)

4. DSICUSSION AND CONCLUSIONS

The approach of settlement analysis applied in this study could simulate well the large consolidation settlement of a thick soft clay deposit, improved by combination of preloading, PVD and vacuum pressure for Sai Gon-Hiep Phuoc (SGHP) project. At this study location, a geotechnical characterization was carefully done to provide input data for settlement analysis. With reference to vacuum pressure distribution, the values of k_p (from 0.85 to 1.0) during various construction stages gave the best estimation of the time-dependent total primary settlement as embankment construction goes. It was detected an increasing trend of k_p with time, which might be explained that for the later stages of loading the vacuum pressure could spread more to the depth. In addition, the smear effect with the ratio between the horizontal permeability of the undisturbed soil and that of the smear zone equal to 3.0 (RS = 3.0) gave the best results in this study settlement analyses.

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