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CETEAU PVD VACUUM SYSTEM IN SOFT BANGKOK CLAY: A CASE STUDY OF THE SUVARNABHUMI AIRPORT PROJECT

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ABSTRACT: A new improvement technique is currently applied for soft Bangkok clay combining capped PVD with vacuum pressure and embankment loading whereby the prefabricated vertical drains (PVD) are connected by PE tubes to a vacuum pump called "CeTeau PVD Vacuum System". The method uses a surface soil layer as a sealing layer for leakage protection and there is no need to place air-tightening geomembrane sheets on the ground surface. This method has two advantages for situations of a) high air/water permeability layer exist near the ground surface, and b) combining vacuum pressure with embankment load. An actual field project combining PVD vacuum and embankment loading has just been completed. The performance data of the system during the improvement of the section EW-4, a part of the third runway of Suvarnabhumi International Airport, Thailand are presented and interpreted. The monitored data indicated that the system mobilized -60 kPa atmospheric pressure. This allowed for unprecedented loading and settlement rates during the construction of an embankment and achieved the required degree of consolidation within the specified time period. The prediction by PVDCON FEM Software generally agreed with the observed values. As expected, increasing the K_h/K_s and OCR values resulted in lower settlement values.

Keywords: Improvement technique, CeTeau PVD vacuum system, staged construction

INTRODUCTION

Vacuum consolidation was proposed in early 1950s by Kjellman (1952) and studies of vacuum induced consolidation continued up to the present (Holtz 1975; Choa 1989; Cognon et al. 1994; Bergado et al. 1998; Tang and Shang 2000; Chai et al. 2006a, b). Vacuum consolidation preloads the soil by reducing the pore pressure while maintaining constant total stress instead of increasing the total stress (Fig. 1). Figure 1 clearly shows the increase of the effective stress as a result of the reduced atmospheric pressure in the soil mass. The net effect is an additional surcharge ensuring early attainment of the required settlement and an increased shear strength resulting in increased embankment stability. The CeTeau system is a new and innovative consolidation system based on the proven concept of vacuum consolidation. The vacuum drainage system (Fig. 2) is for advanced soil improvement whereby the vertical drains are connected via PE tubes to a vacuum pump (Cortlever et al. 2006). The vertical drains were specially developed CeTeau drains type CT-D911 which has a very high resistance against lateral pressure. The CeTeau vacuum PVD system has some big advantages over the standard vacuum drainage systems as follows:

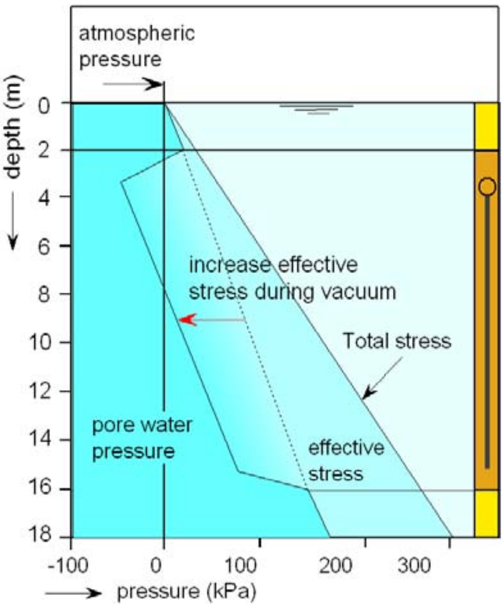

Fig. 1 Increase of effective stress

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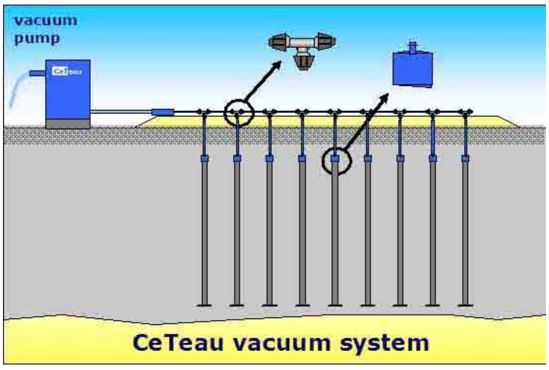


Fig. 2 CeTeau vacuum system

- No liner needed that stay behind in the soil or has to be taken away
- Direct connection of every drain to vacuum pump without flow resistance
- No border trench needed
- No damage possible due to settlements
- Standard drain machines can be used
- No skilled labour needed
- Better control on functioning due to separate testing of the drain sections
- No drainage layer needed

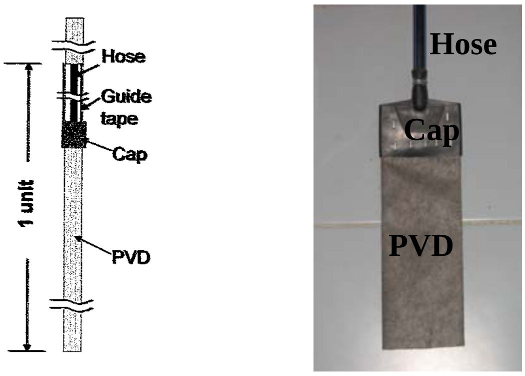
CETEAU VACUUM-PVD SYSTEM

Structure the CeTeau Vacuum System

A CeTeau PVD unit consists of a piece of prefabricated vertical drain (PVD), a drainage hose and a cap connecting the PVD with the hose which it is connected by HDPE tubes as showed in Fig. 3. For the production shown in Fig. 2, the cap has a width the same as the PVD (106 mm), a length of 67 mm, and a thickness of 9 mm. The inside diameter of the hose is about 16 mm. The length of the PVD and the hose will be predetermined based on the information of site investigation and the required CeTeau PVD will be manufactured in a factory and transported to the field. The CeTeau PVD, the collection system, and the vacuum pumps are shown in Fig. 4.

Vacuum and Embankment Loading Consolidation with Ceteau Vacuum PVD

Consolidating a clayey deposit by vacuum pressure with CeTeau PVD is illustrated in Figs. 5a; b. Figure 5b shows the situation when there is a sand layer in the middle of a clayey deposit. To avoid vacuum pressure losses through this sand layer, a sealing sheet is pasted on the filter of the drain passing through the sand layer.



(a) Illustration (b) Actual vacuum PVD

Fig. 3 Structure of CeTeau PVD

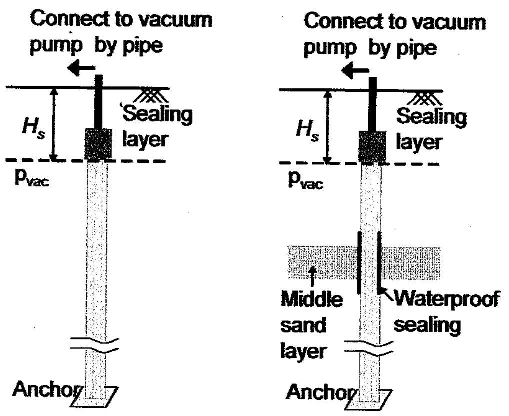
Fig. 4 CeTeau PVD System

Vacuum pressure was applied to the drain through the hose with a maximum value (p_{vac}) at just below the cap. The soil layer above the cap served as sealing layer of p_{vac} at the bottom to zero at the ground surface. The method of installation was the same as the normal PVD installation. An anchor plate was fixed at the end of the CeTeau PVD and installed into the ground through a mandrel.

The thickness of the surface sealing layer (H_s), can be estimated using a simple model, i.e. the vacuum pressure at the bottom of the layer is p_{vac} and zero at the ground surface (Chai et al. 2006b).

$$H_s = \frac{p_{vac}}{\gamma_w Q_a} k_{air} A \qquad (1)$$

where γ_w is the unit weight of water, k_{air} is the permeability to air flow of the sealing layer, A is the area of treatment, and Q_a is the capacity of a vacuum pump.



(a) Without middle sand layer **(b) With a middle sand layer**

Fig. 5 Vacuum consolidation with CeTeau PVD

The increase of the effective stress for a conventional surcharge at time, t_1, can be written according to Eq. (2). When combining the same surcharge with vacuum consolidation the increase in effective stress can be calculated using Eq. (3).

$$\Delta\sigma'(t_1) = U(t_1)\cdot\Delta\sigma_s \tag{2}$$

$$\Delta\sigma'(t_1) = U(t_1)\cdot\Delta\sigma_s + U(t_1)\cdot p_v = U_{eq}(t_1)\cdot\Delta\sigma_s \tag{3}$$

In which $U(t_1)$ is the degree of consolidation at t_1, $\Delta\sigma_s$ is the surcharge, p_v is the vacuum pressure and $U_{eq}(t_1)$ is the equivalent degree of consolidation at t_1.

As $U_{eq}(t_1)$ will exceed $U(t_1)$ for all $t > 0$, the increase of the effective stress for a combination of surcharge and vacuum consolidation will always be more than for a situation with a surcharge only.

Unlike physical loads, the vacuum pressure does not introduce shear stresses in the subsoil as a result of its isotropic character and will, therefore, not cause instabilities. The resulting settlements due to the vacuum loading are also isotropic. The effect of the vacuum consolidation on the loading rate is demonstrated in Fig. 6.

This figure presents the relation between the effective weight of an embankment and the increase of the effective stress during construction. The curved line, constructed from a number of stability calculations, represents the maximum loading line corresponding with a required safety factor (SF = 1.1). The staged loading line depicts 4 stages (or lifts) of an arbitrary loading path including intervening consolidation phases. The 100% consolidation line presents the situation of the effective load equaling the increase of effective stress. The vacuum pressure line runs parallel to the 100% consolidation line at a horizontal distance equal to the vacuum pressure. The maximum excess pore water pressure after placing a lift can be determined by taking the difference between the staged loading line and the 100% consolidation line in case no vacuum is applied. In the case of vacuum consolidation, the excess pore water pressures will be represented by the difference between the staged loading line and the vacuum pressure line. As the rate of consolidation depends only on C_v and the drainage length, dissipation of excess pore water pressures in both cases will require the same time. This implies that the rate of increase of effective stress during vacuum consolidation with surcharge will be more than with just vertical drains and a surcharge. Figure 6 shows that this effect will allow for a higher loading rate.

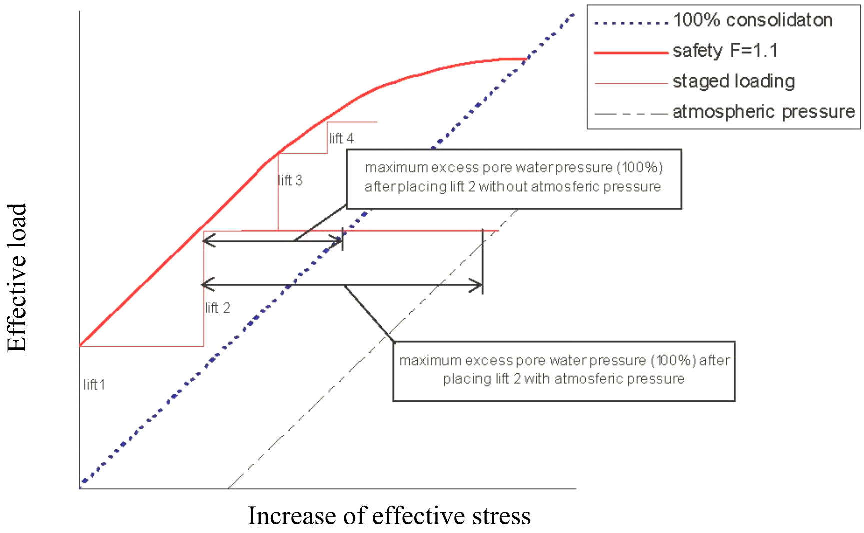


Fig. 6 The relation between the applied (effective) weight of the embankment and the resulting in increase of the effective stress

Settlement Due to Vacuum Consolidation with CeTeau PVD

With the reduction of the consolidation period, it becomes increasingly important to monitor the development of the settlements with time and to accurately predict the final settlement in an early stage of the consolidation process as the time for corrective measures is generally limited. Asaoka (1978) has proposed a simple method to predict the final settlement based on settlement observations at fixed time intervals. By plotting consecutive readings $z(t)$ against $z(t+1)$ a line can be obtained which, over a large interval, can be represented by the linear function :

$$z_{t+1} = \beta \cdot z_t + A \tag{4}$$

where β is the slope of the linear section of the best fit and A is the intersection of the extrapolated section of the linear fit with the Y-axis. A few so-called Asaoka lines, representing various loading stages are been depicted in Fig. 7a.

The intersection point of the extrapolated section of this straight line and the line $z(t)=z(t+1)$ will define the total final settlement at the moment when full consolidation has been reached (see Eq. (5)).

$$Z_{100\%} = \frac{A}{1-\beta} \tag{5}$$

The slope of the plotted line, β_1 can be related to the equivalent consolidation coefficient C_{eq} (consolidation coefficient accounting for the joint effect of the horizontal and vertical drainage of pore water) by applying the following formula:

$$C_{eq} = \frac{-5 \cdot H^2 \cdot \ln\beta}{12 \cdot \Delta t} \tag{6}$$

where H is the length of drainage path (m) and Δt is the time interval.

As demonstrated by Luger et al. (1999), reliable predictions with this method can only be achieved once the degree of consolidation has exceeded 40%. Moreover, as the predicted final settlement also includes secondary settlement continuing linearly with the logarithm of the time, the plotted results tend to deviate from a straight line when the measured settlements become small (i.e. when the degree of consolidation becomes high). To improve the graphical resolution, Luger et al. (1999) have suggested to plot the difference between $z(t+1)$ and $z(t)$ against $z(t)$. In this case, the final settlement is represented by the intersection point of the extrapolated linear fit of the data points with the X-axis $(z(t+1) = z(t))$ (Fig. 7b).

A FIELD PROJECT OF VACUUM AND EMBANKMENT LOADING CONSOLIDATION WITH CETEAU VACUUM PVD

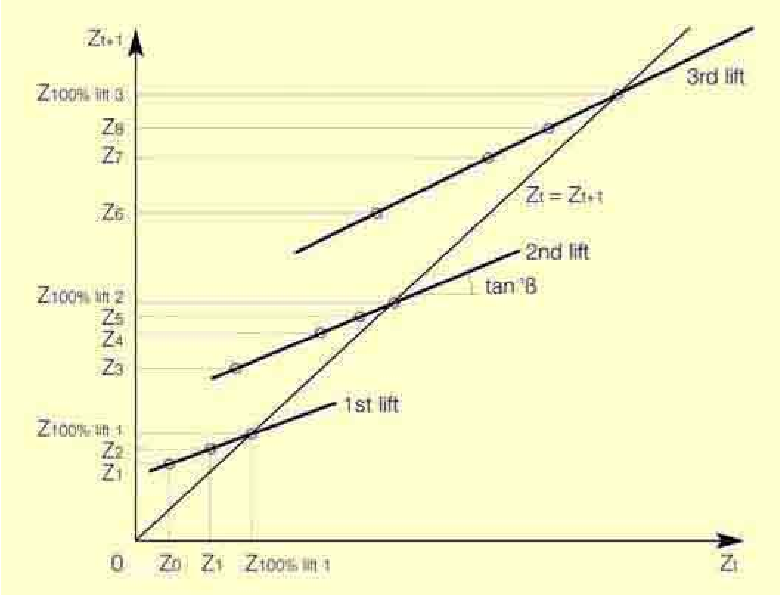
Description of the Project

A project combining vacuum and embankment loading consolidation with BeauDrain-S PVD at Suvarnabhumi Airport, Thailand was reported by COFRA (1996). The soil profile at the site can be divided into 8 sublayers as shown in Table 1 and Fig. 8. It consists of a 2.0 m thick weathered clay layer overlying very soft layer which extends from 2.0 m to 10.0 m depth (very soft clay 1 and very soft clay 2). Underneath the soft clay layer, a 2.0 m thick medium clay layer can be found. The light-brown stiff clay layer can be encountered at 15.0 m to 30.0 m depth. The groundwater level was found at about 0.50 m depth.

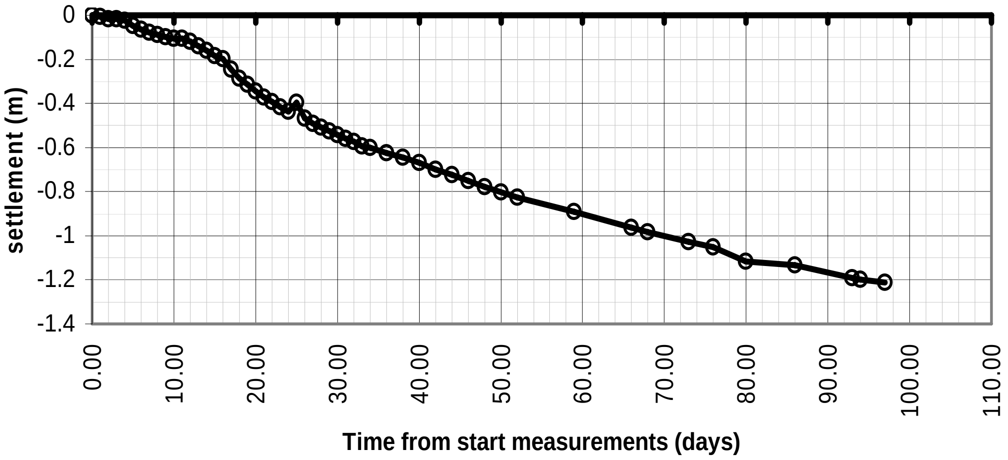
In Table 2, the effective overburden pressure (*POP*) was derived from the given *OCR* value. The numbers are rounded and taken as an average value of each layer. The consolidation coefficient is estimated from an article by Athanasiu et al. (1999). In this article the C_v as function of the effective stress has been back-calculated from settlement data and from a case history on the terrain of the SBIA Project. The CR/C_a correlation is estimated to be 25.

The PVD was installed into 10 m depth with a spacing of 0.85 m and arranged in a triangular pattern (Fig. 9a, b). The instrumentation equipment is installed to monitor the CeTeau system. Only the readings of the piezometers, the vacuum gauges on the pumps, the piezometer outside the drains and the settlement, are discussed in the analysis. All monitoring equipments installed at *EW4* are given in Fig. 10. The following equipments are installed, namely: 2 piezometers (below 5.0 m from ground surface level), 8 settlement plates, and 2 settlement plates for internal use (0.5 m from ground surface level).

The following boundary conditions were used in the design : Installation time of drains = 2 months, maximum pumping time = 4 months, vacuum pressure of -60 kPa, depth of drains 10 m below ground present surface, 60 % consolidation requirement. The embankment was 2.8 m (18 kN/m^3) and Foundation 1.0 m. Embankment was constructed in two phases, namely: Phase 1 (1.5 m, day 0) and Phase 2 (1.3 m, day 14). These assumptions are not based on calculations.



a) Asaoka line



b) Total settlement from Asaoka method

Fig. 7 Asaoka lines and total settlement from Asaoka method

Table 1 The stratigraphy at the site

Present surface	0.00 m	
Water level	-0.50 m	
Type	Top layer (m)	Bottom layer (m)
Top layer, weathered clay	0.00	-2.00
very soft clay1	-2.00	-5.00
very soft clay2	-5.00	-10.00
soft clay	-10.00	-13.00
soft to medium clay	-13.00	-15.00
stiff clay1	-15.00	-17.00
stiff clay2	-17.00	-20.00
stiff clay3	-20.00	-30.00

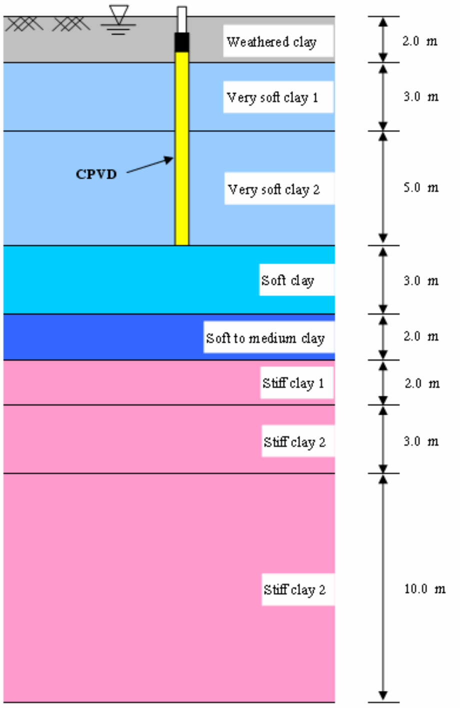
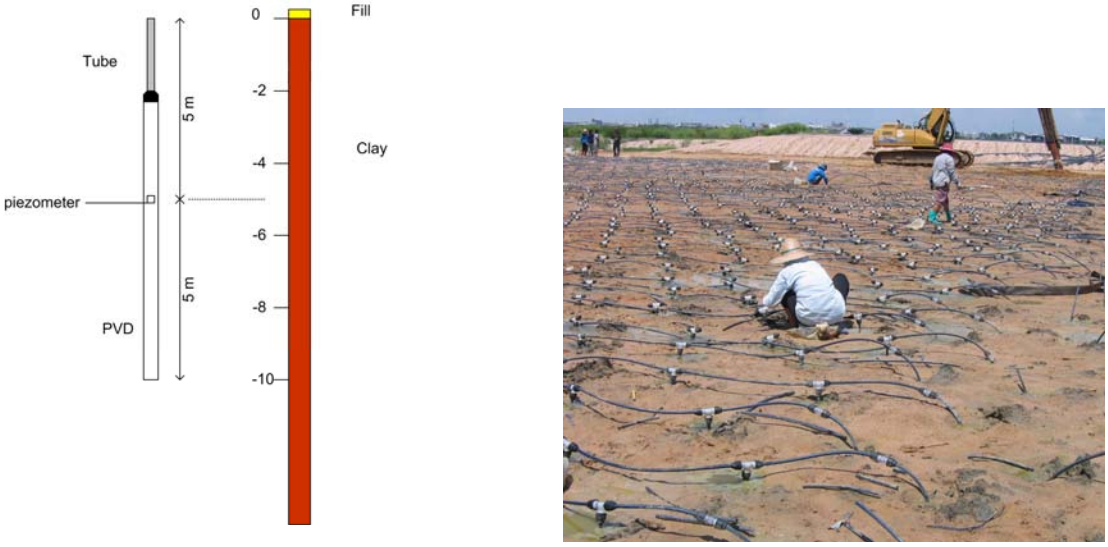


Fig. 8 Soil profile and the depth of BeauDrain-S PVD



(a) The depth of the PVD and piezometer installation (b) The triangular pattern of the PVD

Fig. 9 The depth of the PVD and piezometer installation and the triangular pattern of the PVD

Table 2: The compressibility consolidation parameters

Type	Unit weight [kN/m^3]	Compressibility *RR*	*CR*	C_a	*POP* (kPa)	C_v_theory [m^2/year]
Top layer, weathered clay	18.50	0.035	0.350	0.014	30	-
very soft clay1	13.80	0.050	0.500	0.020	20	0.79
very soft clay2	14.00	0.042	0.420	0.017	30	0.79
soft clay	15.00	0.040	0.400	0.016	60	0.79
soft to medium clay	15.70	0.030	0.300	0.012	80	0.79
stiff clay1	18.50	0.008	0.080	0.003	300	-
stiff clay2	19.00	0.008	0.080	0.003	500	-
stiff clay3	20.40	0.000	0.000	0.000	500	-

Note:

POP = effective overburden pressure

CR = compression ratio

RR = recompression ratio

C_a = creep coefficient

C_v = vertical consolidation coefficient

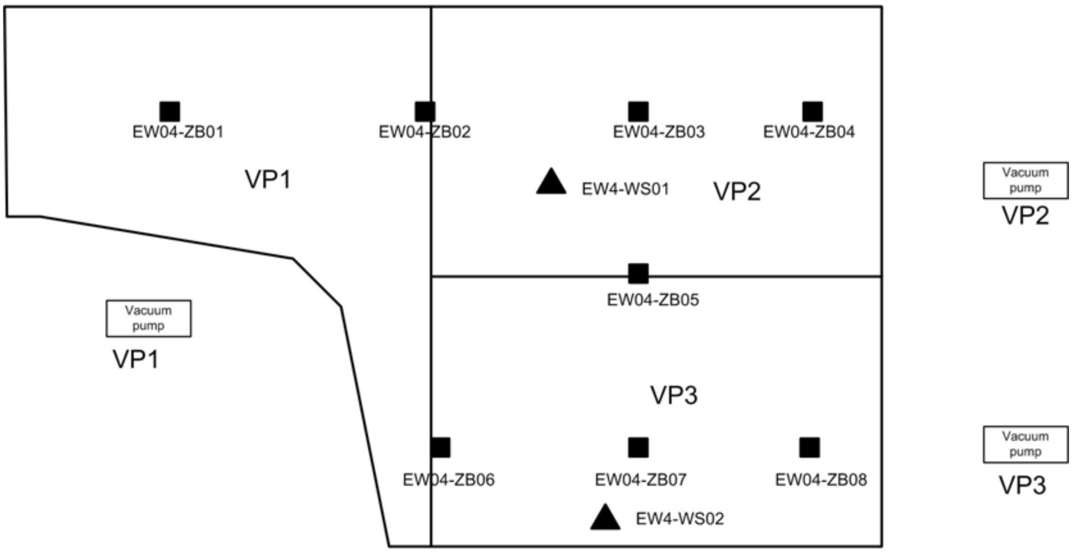


Fig. 10 Layout of the improved area and instrumentation points for EW-4

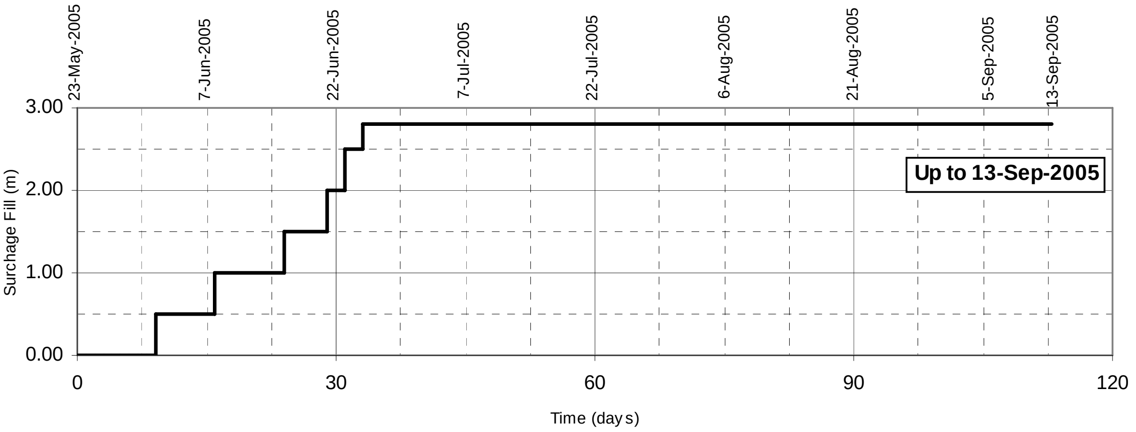


Fig. 11 Variation of total embankment height with time

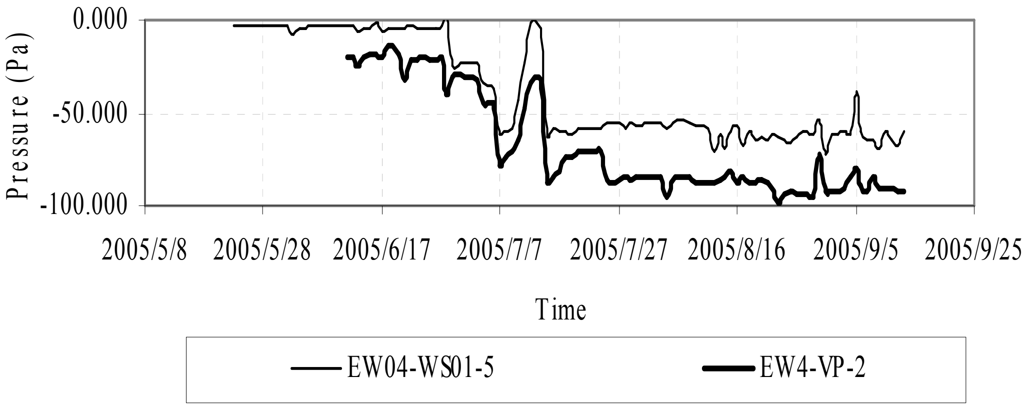


Fig. 12 Variation of vacuum gauge pressure with time with piezometer

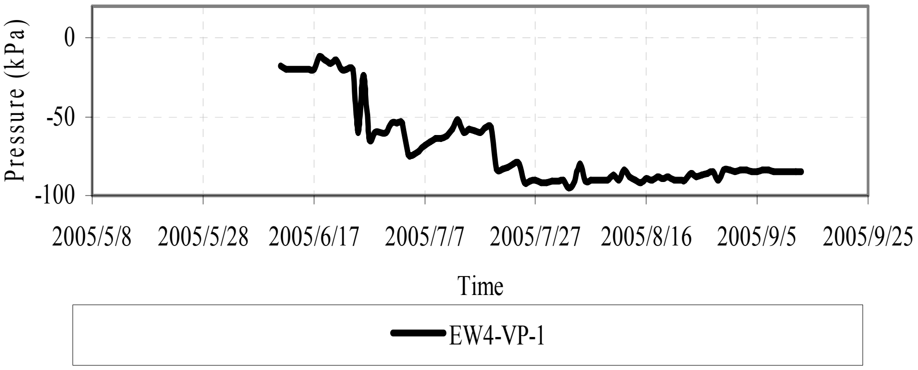


Fig. 13 Variation of vacuum gauge pressure with time with no piezometer

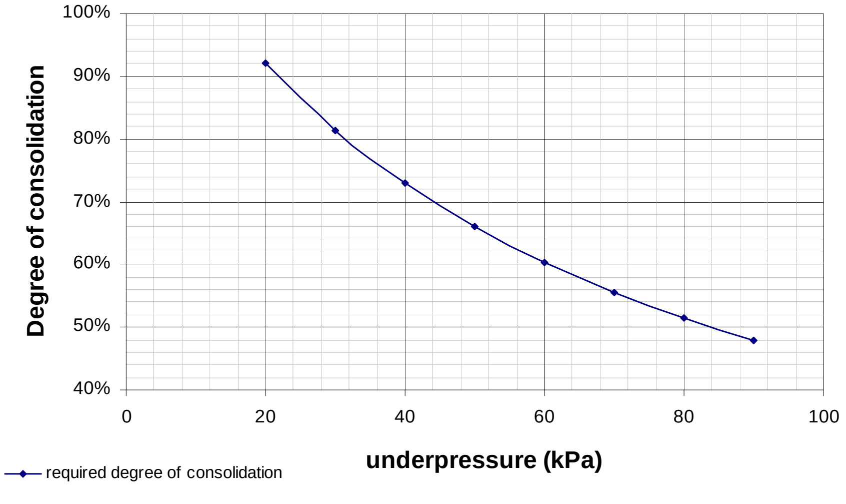


Fig. 14 Relationship between degree of consolidation and under pressure

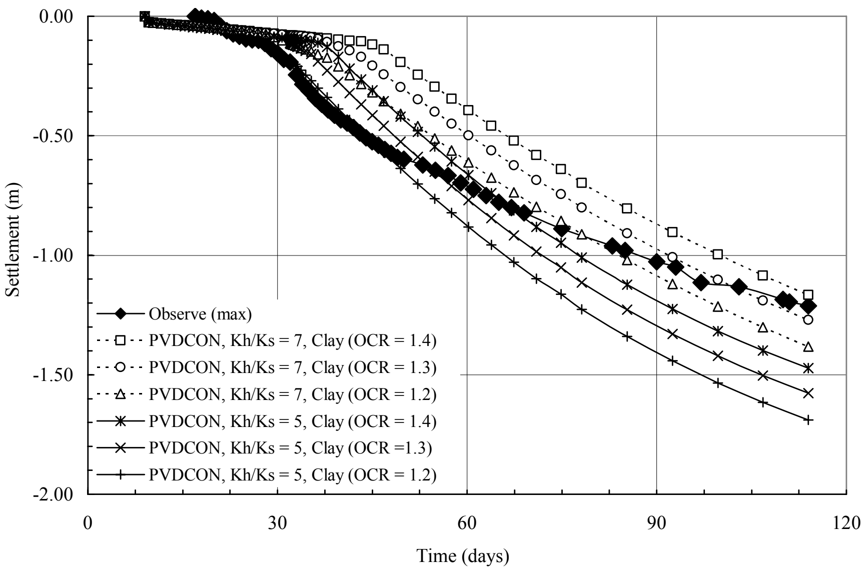


Fig. 15 Settlement from measurement and PVDCON FEM

At the site, the work of installing CeTeau PVD was carried out from May 7 to May 28, 2005. Installation date and initial reading date began on June 8, 2005 and ended on September 13, 2005 (vacuum and embankment loading consolidation). Before starting, a thorough soil investigation was done to check the movement of the settlement plates with the predicted settlements based on calculations of the consolidation process. The area that has to be treated was marked and the level was measured.

If the bearing capacity of the top layer was sufficient, the drain pattern can be set out. If the bearing capacity was not sufficient, a working platform of 0.5m thickness had to be made.

After setting out the drain locations, the installation was started. The drains were prefabricated on length before installation. The CeTeau-Drain, CT-D911, was supplied on rolls of 300 m. They were cut on a length which is 1 m shorter than the layer thickness that had to be consolidated. On one end, an anchor plate was connected to the drain. On the other end a 16 mm HDPE tube was inserted in the drain over a length of 0.5 m. The tube was connected to the drain with steel clips that were attached with electric powered equipment. The tube was able to resist 200 kPa pressure. The prefabricated drains

Table 3 Summary of the Asaoka calculations (values can vary due to incorporation of new measurements and the variability of the Asaoka method)

	Average vacuum on pump during last month	Date measurement	Final settlement	Final settlement based on the Asaoka prediction	Degree of consolidation
	[kPa]	[-]	[cm]	[cm]	[-]
EW4-ZB01	-87	13-9-2005	121	171	71%
EW4-ZB02	-87	13-9-2005	104	157	66%
EW4-ZB03	-89	13-9-2005	115	162	71%
EW4-ZB04	-89	13-9-2005	119	163	73%
EW4-ZB05	-89	13-9-2005	110	147	75%
EW4-ZB06*	-93	13-9-2005	91*	114	80%
EW4-ZB07*	-93	13-9-2005	93*	119	78%
EW4-ZB08*	-93	13-9-2005	101*	125	80%

* Settlement plate located on old canal (thickness of compressible material was less)

were transported from a central assembly plant to the rigs.

The drains were pulled in at the bottom of the mandrel with a rope that was attached to the HDPE until the anchor plate touches the bottom of the mandrel. The mandrel was positioned above an installation point and pushed to the required depth and withdrawn. To be sure that the drain was not partly pulled back the end of the tube that was sticking out has to be measured. If the hole stays open, it was filled with clay slurry to assure that the drains were sealed of from the atmosphere. The crane was operated such that it cannot drive over the tubes to avoid damages. After completion of a determined section, the drains were connected to a central suction tube and tested for air tightness. The configuration of the tubing depends on the shaped and size of the area. After completion of the tubing system, it was tested and repaired if necessary.

Every 3,000 m^2 area was connected to a special vacuum pump that consists of a tank capable of resisting 150 kPa pressure. A 100 m^3 air pump and a 40 to 100 m^3 water pump were connected to the tank to get rid of the air, water vapour and pore water. The water was pumped on the treated area to increase the dead weight of the surcharge and avoid drying out of the top crust. When no surcharge was placed a maximum vacuum of 50 kPa was allowed to avoid formation of water vapour and other gases in the soil. Gases can block the permeability and thus decreased the rate of consolidation. After completion of 2.8 m surcharge, the full vacuum was applied that varied from -70 to -90 kPa at the tank to -50 to -60 kPa at the end of the drain. The pumps provided with a GSM warning system so that disturbance in the suction period was minimized. The pumps operated continuously (168 hours/week) and were tested every week during operation.

Settlement plates were placed between the tubes and were monitored. After completion, the permanent fill of 1.5 m (settlement + final fill + surcharge) was placed. The settlements were measured during the filling stages and after completion of the surcharge until the required settlements were reached. During monitoring, -60 kPa vacuum was maintained in the vertical drains up to a minimum depth of 5 m and created 60% settlement (defined as the ratio of the current settlement to the project final settlement estimated from Asaoka method) while full surcharge and vacuum were applied to the soil, within a period of 6 months.

Results of Measurement

The measured pressures between the start of the measurements and final reading as of 13 September 2005 are presented in this section which followed the construction time (Fig. 11). In this section, only the piezometer readings are given (Fig. 12). The pump pressures with no piezometer attached will be presented in the next section (Fig. 13). The vacuum has increased to -90 kPa under pressure on the pump and a more than -60 kPa inside the drains.

The latest readings of the pump and the piezometer show stabilized data with very high vacuum pressures ranging from -86 kPa to -92 kPa on the pumps at the time when the surcharge reached 2.8 m on 25 June 2005. The total time the pumps were running during this period, almost all pumps were running more than 99% of the time. The acceptance criterion shall be based on the degree of settlement (defined as the ratio of the current settlement to the projected final settlement estimated from the Asaoka method) with a value of no less than 60% while full surcharge and vacuum were applied to the subsoil. To explain how the degree of consolidation was calculated, a short theoretical paragraph is written below. With this theory, areas with a low vacuum pressure can be confirmed using a different degree of consolidation.

The consolidation theory by Terzaghi states that the local degree of consolidation $U_{(z,t)}$ is written as:

$$U_{(z,t)} = (\Delta u_0 - \Delta u_{(z,t)})/\Delta u_0 \qquad (7)$$

The initial excess pore pressure Δu_0 is in this formula equal to the added load, $\Delta\sigma_v$. This means that in the initial situation, with a degree of consolidation of 0%, 0% of the added load is carried by the soil and 100% of the load is carried by the water. In this stage, no settlement has taken place. If a degree of consolidation of 100% is reached, 100% of the added load is carried by the soil, all the excess pore water has dissipated and all the settlement has taken place.

Reworking the formula with the initial excess pore pressure Δu_0 equal to the added load $\Delta\sigma_v$, the formula describing the degree of consolidation can also be written as:

$$U_{(z,t)} = (\Delta\sigma_v - \Delta u_{(z,t)})/\Delta\sigma_v \qquad (8)$$

Equation (8) shows that the degree of consolidation times the added load is equal to the actual percentage the effective stress increase in the subsoil ($\Delta\sigma_v - \Delta u_{(z,t)}$).

If the required acceptance criterion with a degree of consolidation $U_{(z,t)}$ of 60% and a load $\Delta\sigma_v$ of 116 kPa is used, the excess pore pressure $\Delta u_{(z,t)}$ becomes 46 kPa. This means that 116-46 = 70 kPa of the load is carried by the subsoil and the increase of the effective stress $\Delta\sigma'$ in

Table 4 Parameters of PVD related to drain behavior

Item	Unit	Values
Equivalent diameter of the drain, $d_w = (b+t)/2$	mm	51.75
Diameter of the equivalent soil cylinder, $D_e = 1.05S$	m	0.8925
Smear zone diameter, $d_s = 2d_m$	mm	191.49
Hydraulics conductivity ratio, K_h/K_s		5-7
Discharge capacity, q_w	m^3/year	100

Table 5 Parameter of soil for PVDCON analyses (Vacuum pressure = 60 kPa)

Soil No.	Depth (m)	H (m)	C_h (m^2/day)	C_v (m^2/day)	γ (kN/m^3)	w (%)	e_0	C_c	M	OCR	Condition
1	0-2	2	-	-	18.5	50	1.35	0.82	-	5	drain
2	2-5	3	4.329E-3	2.160E-3	13.8	95	2.52	1.76	0.8	1.2-1.4	drain
3	5-10	5	4.329E-3	2.160E-3	14.0	92	2.44	1.44	0.8	1.2-1.4	drain
4	10-13	3	4.329E-3	2.160E-3	15.0	68	1.80	1.12	0.8	1.5	no drain
5	13-15	2	4.329E-3	2.160E-3	15.7	55	1.46	0.74	0.8	1.5	no drain

the soil is 70 kPa. Thus, it can be concluded that the aim of the soil improvement is to increase the effective stress in the soil by 70 kPa. If a lower vacuum pressure is applied to the subsoil than the required -60 kPa under pressure, the calculated increase in the effective stress can be used to calculate the needed degree of consolidation (Fig. 14) is as follows:

Degree of consolidation $U_{(z,t)}$ * (the added load $\Delta\sigma_v$) = increase in effective stress ($\Delta\sigma_v$ -$\Delta u_{(z,t)}$) n this formula, the increase of effective stress is held constant at 70 kPa. This means that when a vacuum pressure of -50 kPa is applied to the subsoil, the needed degree of consolidation with an added load of 106 kPa is equal to 66%.

With the actual settlement and the Asaoka prediction of the final settlement the degree of consolidation can be calculated. Table 3 gives the summary of the Asaoka measurements.

The parameters for soils layer and PVD are listed in the Table 4 and Table, 5 respectively, which were used in PVDCON FEM program (Chai et al. 2006b) to predict settlement for PVD soft ground improvement with vacuum consolidation. The dimensions of PVD and mandrel were 100x3.5 mm and 120x60 mm, respectively.

The maximum settlements of experimental area EW-4 has reached 1.21 m with a degree of consolidation of 80% (Fig. 15). The final settlements from PVDCON program with varied K_h/K_s values of 5 and 7 and varied *OCR* values are plotted together with the observed values in Fig. 15. The settlements tend to be larger when lower values of K_h/K_s and lower values of *OCR* are utilized. Overall, the predictions agreed with observed values.

CONCLUSIONS

Based on the data and results of the analyses, the following conclusions can be made:

1) The Ceteau PVD Vacuum System is a new improvement technique and was currently applied for soft Bangkok clay combining capped PVD with vacuum pressure and embankment loading whereby the prefabricated vertical drains (PVD) are connected by HDPE tubes to a vacuum pump. No need to place air-tightening geomembrane sheets on the ground surface.

2) This method has two advantages for situations when: a) high air/water permeability layer exists near the ground surface, and b) combining vacuum pressure with embankment load.

3) Average vacuum pressure of -50 to -60 kPa at PVD and -70 to -90 kPa at the vacuum pump were obtained.

4) The final settlement 0.91 m and 1.21 m with a degree of consolidation of 66% to 80% were achieved.

5) The predictions using the PVDCON FEM Software generally agreed with the observed values. As expected, increasing the K_h/K_s and OCR values tend to decrease the magnitudes of settlements.

6) The CeTeau PVD Vacuum System reduced the time of consolidation by more than 50 %.

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