Application of prefabricated vertical drain (PVD) combined with vacuum and heat preloading for soft Bangkok clay improvement

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ABSTRACT: This paper presents the combination of prefabricated vertical drain (PVD) with vacuum and heat preloading in accelerating the consolidation process for soft Bangkok clay improvement. The laboratory tests were conducted in small scale consolidometer with undisturbed specimens using PVD combined with surcharge (PVD only), PVD combined with surcharge and vacuum pressure (Vacuum-PVD) and PVD combined with surcharge and heat up to 90°C (Thermo-PVD). Analyses were carried out to determine the flow parameters by back-calculation using Hansbo (1979) methods. From the laboratory tests, the C_h values for undisturbed samples with PVD, vacuum PVD and thermal PVD were 2.34, 2.42 and 2.63 m^2/yr, respectively, with corresponding k_h/k_s values of 5.1, 4.7 and 4.5, respectively. The increased hydraulic conductivity of the smear zone of undisturbed specimens using Vacuum-PVD and Thermo-PVD resulted in the increase in C_h by 2% and 13% and the decrease in k_h/k_s of about 11% and 12%, respectively. The increased hydraulic conductivity due to vacuum pressure increased the horizontal coefficient of consolidation of PVD that was higher than using only PVD improvement. In addition, higher temperatures less than the boiling point of water resulted to decreased viscosity of water within the smear zone surrounding the PVD which largely attributed to the increase in the soil hydraulic conductivity especially at the smear zone.

1 INTRODUCTION

The prefabricated vertical drains (PVDs) technique is a method of soft ground improvement to increase soil strength, reduce soil compressibility and increase soil stiffness. For this method, the installation of the PVDs in the clay reduces the length of the drainage paths due to pore water can flow faster in the horizontal direction toward the drain, and then flow freely along the drain vertically towards the permeable drainage layers. Pore water squeezed out during the consolidation of the clay resulted the hydraulic gradients created by preloading. Thus, PVDs method reduces the time to reach the required degree of the consolidation. Consequently, the higher horizontal permeability of the clay is also utilized (Hansbo, 1979, 1981, 1987, 1997; Bergado et al., 1991). Normally, a surcharge preloading equal to or greater than the expected loading is applied over the soft ground to accelerate the consolidation process by accelerated drainage through the vertical drains and shorten the drainage paths. To decrease the problem of instability, the PVD preloading with embankment surcharge can be combined with vacuum pressure which was proposed in the early 1950 by Kjellman (1952). The 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; Bergado et al., 2006; Saowapakpiboon et al. 2008a,b). Vacuum consolidation helps to reduce the pore pressure while maintaining constant total stress and then, the effective stress is increased due to 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. Moreover, PVD application combined with heat preloading was first proposed Abuel-Naga et al. (2006) by using the thermal treatment up to 90°C combining with PVD called Thermo-PVD. Due to the effect of temperature on the coefficient of the hydraulic permeability was also studied previously (e.g. Towhata et al., 1993;Morinl and Silva 1984; Houston and Lin 1987; Burghignoli et al. 1995; Delage et al., 2000) who reported that the hydraulic conductivity of soil increased with increasing the temperature. The Thermo-PVD can remove the smear zone and, consequently, faster rate of consolidation was achieved due to the elevated temperature resulted in an increase in shear strength and a decrease in water content. Thus, the smear zone can offset the effect of disturbance due to the PVD installation by thermally induced increase in permeability of soils around a heat source.

2 PVD IMPROVED WITH VACUUM AND HEAT IN THE LABORATORY TEST

The small consolidometer used for undisturbed specimens have dimensions of a 200mm in diameter and 300mm in height. There were 3 types of PVD installations namely; PVD only, Vacuum-PVD and Thermo-PVD as shown in Figs. 1a,b,c. Geotextiles were placed at the bottom and top of the soil samples. The apparatus composed of loading system and triangular or rectangular steel frame support as well as steel plate on the top of the small consolidometer cell.

Vacuum pressure was generated from vacuum pump to apply to consolidometer cell which -15 kPa for undisturbed sample. The water generated from suction by vacuum pressure of both samples was stored in a closed container.

The flexible wire heater was used as heat source that was connected to the PVD to transfer the heat throughout PVD length. A thermo-couple was connected to the thermostat that can record the temperature up to 120ºC at the center of the sample. Thermo-couples of each radial distance were used to monitor the heat transfer in the specimen during the test by digital data logger. The thermostat was used to maintain the supply of heat and automatically shut down upon reaching the specified amount of heat. Both heater wire and thermo-couple were connected to the thermostat which was programmed with two functions, namely: to transfer heat to the heaters at the desired temperature and to keep that temperature constant, as monitored by the readings taken by the thermocouple with an accuracy of ± 0.1ºC.


(a) (b) (c)

Figure 1. Small scale consolidometer for undisturbed specimens; (a) with PVD, (b) with Vacuum-PVD and (c) with Thermo-PVD

A laboratory vane shear apparatus, capable of measuring shear strengths at different locations and depths, was used to determine the undrained shear strengths before and after the tests at radial distances of 20mm, 45mm and 90mm. The vane blades, made of stainless steel, were 20mm in diameter and 40mm in height. It was attached to an adjustable stainless steel rod and could be adjusted to locate measurement points within the specimen. The maximum torque was determined electronically.

The soil samples were obtained from site of the Second Bangkok International Airport (SBIA) which is located 30km southeast of Bangkok. The soft clay samples were collected from 3.0 to 4.0 m depths below weathered crust layer. Table 1 shows the physical properties of the soft Bangkok clay. The PVD material used was CeTeau drain CT-D911 which is summarized in Table 2.

Table 1. Physical properties of soft Bangkok Clay

Physical properties	
Liquid limit (%)	102.24
Plastic limit (%)	39.55
Water content (%)	112.69
Plasticity index	62.69
Total unit weight (kN/m^3)	14.70
Specific gravity	2.66

Table 2. Summary of CeTeau drain properties (CT-D911)

Drain Body	configuration	├┼┼┼┼┼┼┼┤
	material	Polypropylene
	channels	44
Filter Jacket	material	Polypropylene
	colour	grey
Weight (g/m)		78
Width (mm)		100
Thickness (mm)		3.5

The undisturbed specimens were extruded from a 254mm (diameter) piston sampler and trimmed into the 200mm diameter specimen for the small consolidometer cell. The undisturbed specimens in the small consolidometer were consolidated, under a vertical stress of 30 kPa, after the PVDs were installed into the specimens. The 30 kPa surcharge load was applied in the specimen with PVD only. The 15 kPa surcharge load combined with -15 kPa vacuum pressure was applied pressure in the specimen with Vacuum-PVD. The temperature in specimen using Thermo-PVD was heated up to 90ºC combined with the application of surcharge load of 30 kPa.

3 Back calculation C_h values

From the settlement observation, the final settlement S_f is determined by the method of Asaoka (1978). The coefficient of consolidation is back calculated by the method of Hansbo (1979), C_h is back calculated from the following relationships when $U_h = 90\%$.

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

where U_h is the degree of consolidation for horizontal drainage; T_h is the time factor for horizontal drainage; F is the factor which expresses the additive effect due to the spacing of the drains, F(n), smear effect, F_s, and well-resistance, F_r. The values of F(n), F_s and F_r are given by the following equations:

$$F(n) = \ln\left[\frac{D_e}{d_w}\right] - \frac{3}{4}$$

$$F_s = \left[\frac{K_h}{K_s} - 1\right] \ln\left[\frac{d_s}{d_w}\right]$$

$$F_r = \pi z (L - z) \frac{K_h}{q_w}$$

$$F = F(n) + F_s + F_r$$

where D_e is the diameter of the equivalent soil cylinder, d_w is the equivalent diameter of the drain, K_h is the coefficient of horizontal permeability, K_s is the horizontal permeability of the smear zone, d_s is the diameter of the smear zone, z is the distance from the drainage end of the drain, L is the length of the drain for double drainage and twice the length of the drain for single drainage, q_w is the discharge capacity of the drain at hydraulic gradient of 1 (one). The time factor, T_h, for horizontal drainage can be calculated using:

$$T_h = \frac{C_h t}{D_e^2}$$

where C_h is the coefficient of horizontal consolidation and t is the time elapsed after the application of the load.

4 TEST RESULTS AND DISCUSSIONS

4.1 *Settlement*

Figure 2 shows the differences in the rates of settlement and the final settlements of small consolidometer of undisturbed specimens improved with PVD, Vacuum-PVD and Thermo-PVD. The results showed that the undisturbed specimens with Thermo-PVD has the highest volume contraction and rate of consolidation due to thermal effects. Specimens improved with PVD only and the Vacuum-PVD have smaller final settlements and smaller rates of settlement than the Thermo-PVD. While, the final settlement of specimen with PVD only is equal to that of specimen with Vacuum-PVD. For the undisturbed specimen with PVD only, the final settlement was approximately 4.3mm in about 21 days. The specimen with the Vacuum-PVD indicated a settlement of 5mm in about 21 days. The specimen treated Thermo-PVD had the highest settlement of approximately 10 mm around 17 days.

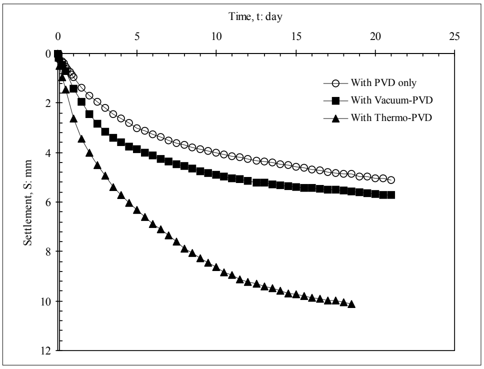


Figure 2. Comparison of consolidation curves of undisturbed specimens in small consolidometer

In addition, the specimen with the Vacuum-PVD had higher rate of settlement than the specimen with the PVD only in the initial stage. It seems that the vacuum preloading increased the coefficient of horizontal hydraulic permeability. For the Thermo-PVD, the drainage point is located at the center of the maximum temperature zone that help faster dissipation of the thermally induced pore water pressures. Moreover, the existence of drainage point in the center of the maximum temperature zone enhances the consolidation rate since the soil coefficient of hydraulic permeability of smeared zone around drainage point increased significantly with temperature. Thus the reduction in water content is greatest close to the Thermo-PVD (heat source) and decreased with the distance away from the heat source.

4.2 *Heat transfer*

The temperature variation with time of both undisturbed specimens in the small cylinder cell are illustrated in Fig. 3. The temperature in the undisturbed specimens was close to 90ºC at r=20mm and around 70ºC at r=90mm. The temperature decreased with distance from the heat source. However, for a normal mandrel dimension of 60mm x 120mm, the equivalent radius of the smear zone is around 50mm, which is within the zone of significant temperature increase. This increase in temperature of the smear zone increased the coefficient of hydraulic permeability of the clay mainly due to the decrease in the viscosity of water.

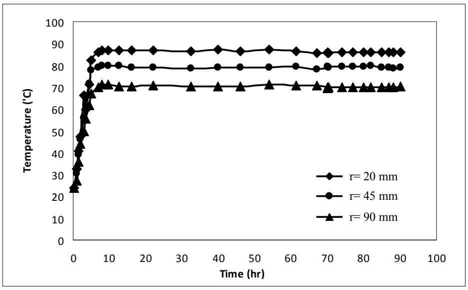


Figure 3. Heat transfer of small consolidometer in undisturbed sample

4.3 *Shear strength and water content*

Water content reductions occurred with the increase in temperature and application of vacuum pressure combined with PVD as shown in Fig. 4. High reduction of water content occurred within 2.5 times the equivalent radius of Thermo-PVD and 2 times of the diameter of the smear zone. Similar phenomenon was observed in Vacuum-PVD treated specimen although with smaller reduction in the water content than Thermo-PVD. The greater reduction in moisture contents adjacent to Thermo-PVD can be attributed to the thermally induced excess pore pressures because the thermal expansion coefficient of the pore water is approximately 15 times larger than the thermal expansion of the clay solid skeleton (Abuel-Naga et al, 2006b) Subsequently, the build up of the excess pore pressure can be easily disposed by the Thermo-PVD.

The shear strength increased with increasing temperature as shown in Fig. 5. The largest increase in the shear strength occurred within the 2 times the equivalent radius of the PVD. A similar phenomenon was observed in the Vacuum-PVD treated specimen although with smaller strength gain when compared to the results from Thermo-PVD.

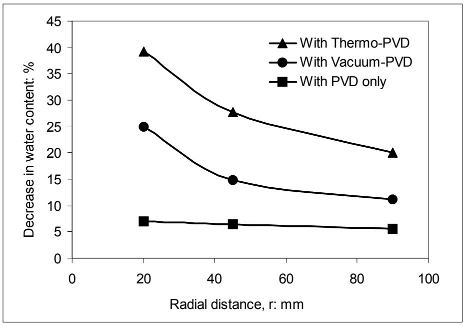


Figure 4. Relationship between decrease in water content and radial distance of undisturbed specimens in small consolidometer

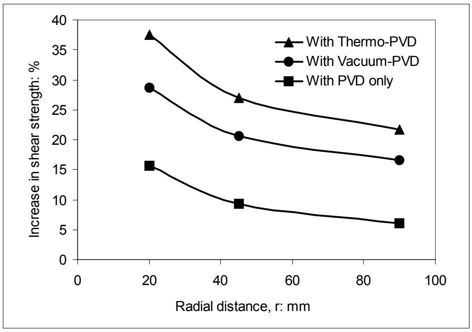
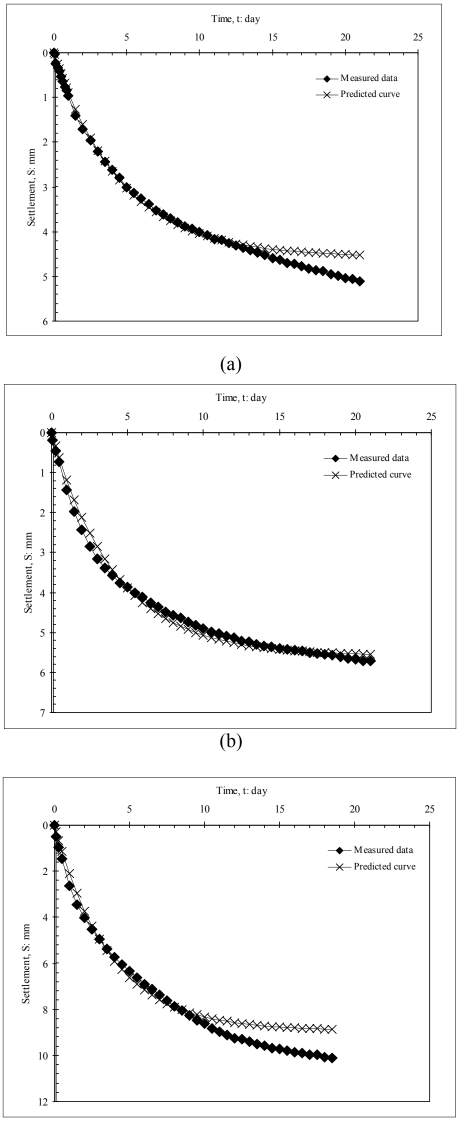


Figure 5. Relationship between increase in shear strength and radial distance of undisturbed specimens in small consolidometer

4.4 *C_h and K_h/K_s values*

The measured and the theoretical time settlement curves of small consolidometer for the undisturbed specimens are plotted in Figs. 6a,b,c for PVD only, Vacuum-PVD and Thermo-PVD, respectively. The values of C_h and k_h/k_s for the specimen with PVD only are 2.40 m^2/yr and 5.1, respectively, as shown in Fig. 6a. For the specimen with the Vacuum-PVD, the corresponding values are 2.43 m^2/yr and 4.6, respectively, as demonstrated in Fig. 6b. For the specimen with the Thermo-PVD, the corresponding values are 2.70 m^2/yr and 4.5, respectively, as demonstrated in Fig. 6c. Consequently, the use of Vacuum-PVD and Thermo-PVD increased the hydraulic conductivity of the smear zone resulting in the increase in C_h by 2% and 13% and the decrease in k_h/k_s of about 11% and 12%, and, respectively.



(a)

(b)

(c)

Figure 6. The observed and predicted curves for settlements to determine C_h values for the undisturbed specimens improved with (a) PVD only, (b) Vacuum-PVD and (c) Thermo-PVD

The values of C_h and k_h/k_s for the undisturbed specimens improved with PVD only, Vacuum-PVD and Thermo-PVD are summarized in Table 4.

Table 4 Summary of changes in flow parameters for specimens in small consolidometer

Flow Parameters	Only PVD	Vacuum-PVD	Thermo-PVD
C_h (m^2/yr)	2.40	2.43	2.70
K_h/K_s	5.10	4.60	4.50

5 CONCLUSIONS

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

1) For the Thermo-PVD improvement, the consolidation rate was faster and the settlements was larger compared to the Vacuum-PVD improvement. The sample with PVD only had the lowest settlement rate whose the magnitude of the final settlement was equal with the Vacuum-PVD.

2) The back-calculated C_h values for undisturbed samples with PVD, Vacuum-PVD and Thermo-PVD were 2.40, 2.37 and 2.70 m^2/yr, respectively with the corresponding k_h/k_s values were 5.1, 4.6 and 4.5, respectively. The increased hydraulic conductivity of the smear zone of Vacuum-PVD and Thermo-PVD resulted in the decrease in k_h/k_s of about 11% and 12%, and the increase in C_h by 2% and 13%, respectively.

4) The reduction of water content occurred with the increase in temperature and vacuum pressure around the PVD core.

5) The shear strengths increased with increasing temperatures and decreasing water contents. The largest increase in the shear strength was within smear zone at distances up to 2 times of the equivalent radius of the mandrel.

6) The hydraulic conductivity of the smear zone increased due to heat and vacuum effects. For the specimen with Thermo-PVD and Vacuum-PVD, k_h/k_s values slightly decreased while the coefficient of horizontal consolidation, C_h, increased.

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