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COMPARISON ON THE PERFORMANCE OF PREFABRICATED VERTICAL DRAIN (PVD) PRELOADING COMBINED WITH AND WITHOUT VACUUM AND HEAT

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ABSTRACT: This paper focus on performance of prefabricated vertical drain (PVD) preloading combined with and without vacuum and heat to accelerate the consolidation of soft Bangkok clay. The laboratory tests were conducted using reconstituted specimens in large scale consolidometers combined with and without vacuum and heat. The flow parameters were back calculated in terms of the horizontal coefficient of consolidation (C_h) and the ratio between the horizontal permeability in undisturbed zone (k_h) to the horizontal permeability in smear zone (k_s) or (k_h/k_s) based on Hansbo (1979) method. The back-calculation analysis results show that the combination of vacuum pressure and heat can increase the horizontal coefficient of consolidation, C_h of 126.42% and decrease of k_h/k_s of 63.33%. Furthermore, vacuum can increase higher rate of consolidation temperature can decrease viscosity of pore water by reducing the drainage retardation effects in the smear zone around the PVD which resulted in faster rate of consolidation and higher magnitude of settlement.

Keywords: Prefabricated vertical drain, consolidation, viscosity, drainage

INTRODUCTION

Prefabricated vertical drains (PVDs) with preloading is a method of soft ground improvement which is environmental friendly compared to deep admixture method due to basic soil properties are not changed. Popular advantages of this method are economization and simplicity due to no need for heavy construction machines. This method is developed for surcharging method by inserting prefabricated vertical drains due to the advantage in term of horizontal hydraulic conductivity is greater than the vertical conductivity to shorten consolidation time (Hansbo 1979, 1981; Bergado et al. 2002; Shen et al. 2005). The principle of this method is squeezing the pore water out during the process of consolidation which preloading help to create the hydraulic gradients. Thus, the pore water can flow in toward the drain in the horizontal direction, and then flow freely along the drain vertically towards the permeable drainage layers on ground surface. Usually, a surcharge load equal to or greater than the expected loading is applied over the soil surface to generate the necessary hydraulic gradient needed for vertical drainage through the PVDs. Application of PVDs method is widely used in soft ground improvement. However, the PVD installation using a mandrel causes disturbances in the clay surrounding the PVD resulting in lower horizontal hydraulic conductivity in the smear zone. (Hansbo 1979, 1981, 1987, 1997; Bergado et al. 1991; Indraratna and Redana 1998; Sharma and Xiao 2000). Moreover, the disadvantage of PVDs with embankment surcharge preloading is the instability problem that limited the height and the slope of the embankment. PVDs with embankment preloading combined with vacuum pressure (called Vacuum-PVD) has been utilized to minimize the instability problem and to accelerate the rate of consolidation. Kjellman (1952) first proposed the vacuum consolidation in early 1950s. Subsequently, the studies of vacuum consolidation continued up to the present (Holtz 1975; Choa 1989; Cognon et al. 1994; Bergado et al. 1998; Tang and Shang. 2000; Bergado et al. 2006; Chai et al. 2006a, b, 2008; Saowapakpiboon et al. 2008a, b, 2009, 2010). Vacuum consolidation can reduce the pore pressure and maintain constant total stress instead of increasing the total stress. The effective stress is increased due to the reduced (less than atmospheric) pressure in the soil mass. In addition, the horizontal hydraulic conductivity in

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smear zone, k_s, around the PVD increases with heat application which was first proposed by Abuel-Naga et al. (2006). This technique is called "Thermo-PVD" by using the thermal treatment up to 90°C combining with PVD. The PVD combined with heat works by the reduction of the smear effect due to the increased clay permeability at elevated temperature. Consequently, faster rate of consolidation was achieved but with larger magnitude of settlement (Pothiraksanon et al. 2007, 2008). The effect of temperature on the horizontal hydraulic conductivity was also studied previously and reported that the hydraulic conductivity of soil increased with increasing the temperature. The porosity decreases when thermal conductivity of soft clay increases.

TEST EQUIPMENTS

Large Consolidometer

The new large scale consolidometer consists of a cylinder cell of 0.45m in inner diameter and 0.95m in height made of polyvinyl chloride (PVC) with a thickness of 10 mm rested on steel base which can resist pressure less than 500 kPa as shown in Fig.1. The upper and lower pedestal with a thickness 40mm were connected by eight steel rods of 12mm. The piston system consisted of a piston of 40mm in thickness and a hollow shaft with outside diameter of 100 mm. To prevent the tilting of the piston, a guide was installed on the upper pedestal around the shaft and was fixed with the upper pedestal with eight steel bolts of 15mm. Silicon grease lubricated "O" rings were sealed between the upper pedestal and the cylinder cell, between the lower pedestal and the cylinder cell, between the piston and the cylinder cell, between the shaft and the upper pedestal and between the guide and the shaft. The air pressure was applied through the upper pedestal to the top of the piston and the vacuum pressure is applied through the shaft of the piston to the bottom of piston and the PVD cap, respectively. Air pressure was transformed to vacuum pressure by a vacuum generator which was connected directly with an air pump during consolidation test. A natural rubber membrane with a thickness of 3mm was installed in the chamber above the piston to prevent the leakage of the air pressure and/or vacuum pressure through the piston. The natural rubber membrane was folded in vertical direction initially to allow the vertical displacement of the piston during consolidation. Geotextiles were placed on top and bottom of the soil specimens to prevent clogging of the loading piston. Dial gauges were placed on top of the shaft for settlement measurements. A pore pressure

Fig. 1 Large scale consolidometer

transducer was installed and connected with data logger to monitored pore pressure in the specimen during consolidation.

Heat Source

Flexible heater wire with a capacity of 120°C and power of 6W per meter was attached to the PVD for the reconstituted specimen improved with Thermo-Vacuum PVD as shown in Fig. 2. Thermocouples were installed at radial distances of 25, 50, 100 and 200 mm far from PVD and were connected to the digital data logger to monitor the temperature and heat transfer during the consolidation test. Before and after the laboratory tests, the water contents and shear strengths were also measured at the aforementioned locations, the temperature sensor boxes were used to maintain the heat temperature at heat source and shut down automatically upon reaching the controlled heat of 90°C, at the heat source.

Vane Shear Apparatus

Customized vane shear equipment was used to measure the undrained shear strength before and after

Fig. 2 PVD combined with cap-PVD and flexible heater wire

consolidometer tests. The vane blade made of stainless steel, is 20mm in diameter and 40mm in height. It is attached to an adjustable stainless steel rod 5mm in diameter, capable of measuring the shear strengths at different locations and depths. The rod was held in place by a removable rectangular steel adapter above the circular plate rotator. The adapter was connected to the force sensor, which was attached on top of the circular rotator when the vane is turned. The force sensor was connected to the transducer to determine the readings. The maximum torque of each radial distance was calculated by multiplication of force and radial arm distance. The vane shear tests were done at radial distances of 25mm, 50mm, 100mm and 200mm, respectively. The schematic diagram for laboratory vane shear apparatus was shown in Fig. 3.

Vacuum Generator

The vacuum generator was utilized to transform the air pressure to vacuum pressure. This apparatus was connected directly with air pump during consolidation test. The water generated from suction by vacuum pressure was stored in a closed container.

Excess Pore Pressure Transducer

A KPD-200 kPa excess pore pressure transducer was connected with data logger to monitor the pore pressure in the specimen during consolidation using a probe inserted into the wall of the consolidometer cell at the desired level. The excess pore pressures were monitored in the consolidometer test by using the digital data logger.

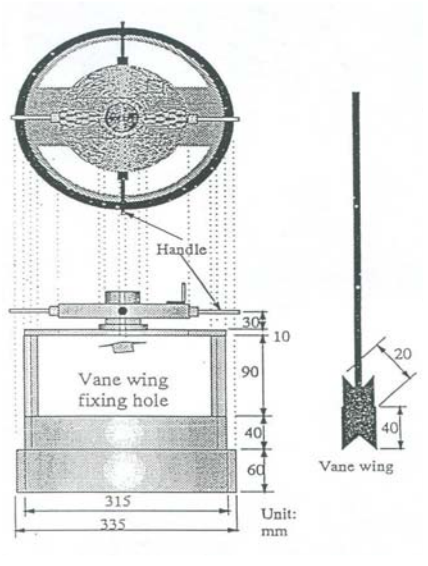


Fig. 3 Schematic of laboratory vane shear apparatus

TESTING PROCEDURES

Test Specimen

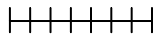
The soil samples used in this study were obtained from a site which is located at the area of Second Bangkok International Airport (SBIA), Thailand. The soft clay samples were collected from 3.0 to 4.0m depths. Disturbed samples were obtained by digging the soils up to required depth with a backhoe. Then, the disturbed soil samples were placed in covered plastic containers for storage. Undisturbed samples were collected by 10 inches piston samples and immediately covered with wax after sampling to prevent loss of moisture. The physical properties of the soft Bangkok clay are shown in Table 1. The PVD material used was CeTeau drain (CT-D911). The PVD properties are summarized in Table 2.

The disturbed samples were mixed by using a mixer. Water was added until the water content was slightly greater than the liquid limit. The mixed soil was placed into the large scale consolidometer cell layer by layer until to the desired height. The appropriate loads were applied for the reconstitution process to obtain the

Table 1 Physical properties of soft Bangkok Clay at 3-4 m depth in Suvarnabhumi airport

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 General properties of CeTeau drain (CT-D911)

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

desired water content and void ratio equal to the initial conditions.

Consolidometer Test Program

For the reconstitution using the new large consolidometer, a 50 kPa pressure was applied. Drainage was allowed to flow to the top and bottom of the apparatus. Silicone grease was applied to the insides of the large consolidometer to reduce the friction. Throughout the whole process, the settlements were monitored. After reconstitution, the water content and shear strength, and specimen height were determined.

The vertical pressure of 50 kPa was increased to 100 kPa after reconstitution under the applied vertical pressure in the specimen improved with PVD. For the Thermo-Vacuum-PVD, the specimen was improved with PVD combined with heat up to 90 ºC together with vertical pressure of 50 kPa and vacuum pressure of -50 kPa. The temperatures were controlled by an electronic thermal-control unit that received the signal from thermocouples. Drainage was allowed to flow only one way. Settlement was monitored during the test until the soil specimen reached to 90% consolidation. The method of Asaoka (1978) was used to estimate the degree of consolidation and the magnitude of final settlement.

Effect on the Coefficient of Consolidation, C_h, and Permeability Ratio, k_h/k_s

The values of C_h for all tests were back-calculated using the equations from Hansbo (1979) for radial consolidation with PVD is given as follows:

$$U_h = 1 - \exp\left[\frac{-8T_h}{F}\right] \tag{1}$$

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:

$$F = F(n) + F_r + F_s \tag{2}$$

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

$$F_s = \left(\frac{k_h}{k_s} - 1\right) \cdot \ln\left(\frac{d_s}{d_w}\right) \tag{4}$$

$$F_r = \pi \cdot z \cdot (L - z) \cdot \left(\frac{k_h}{q_w}\right) \tag{5}$$

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:

$$T_h = \frac{C_h t}{D_e^{\,2}} \tag{6}$$

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

The increase in the average coefficient of horizontal consolidation due to the temperature and/or vacuum effect on horizontal permeability in the smear zone can be calculated as follows:

$$(k_s)^{Thermo-Vacuum\,PVD} = [\left(\frac{k_h}{k_s}\right)^{PVD} \left(\frac{k_s}{k_h}\right)^{Thermo-Vacuum\,PVD} \frac{(k_h)^{Thermo-Vacuum\,PVD}}{(k_h)^{PVD}}](k_s)^{PVD} \tag{7}$$

where $(k_s)^{\text{Thermo-Vacuum PVD}}$ is the horizontal permeability of the smear zone of Vacuum-PVD or Thermo-PVD or Thermo-Vacuum-PVD, $(k_h)^{\text{PVD}}$ is the horizontal permeability of PVD and $(k_h)^{\text{Thermo-Vacuum PVD}}$ is the horizontal permeability of Thermo-Vacuum-PVD and $(k_s)^{\text{PVD}}$ is the horizontal permeability of the smear zone of PVD.

TEST RESULTS AND DISCUSSIONS

Consolidation Behavior of Tested Samples

The comparison of settlement of specimens improved with and without vacuum and heat in the large scale consolidometers test are shown in Fig. 4. The specimen improved with Thermo-Vacuum-PVD has higher rate of settlement and more settlement than the specimen improved with PVD. Thus, applying vacuum and heat to the clay specimen can increase the coefficient of horizontal consolidation and the permeability.

Heat Transfer

The heat transfers in the soil specimens at specific temperatures with respect to the specific distances from PVD were observed. Flexible wire heaters attached to the core of PVD were used as heat source to increase the temperature up to 90ºC. Temperatures of the heat source

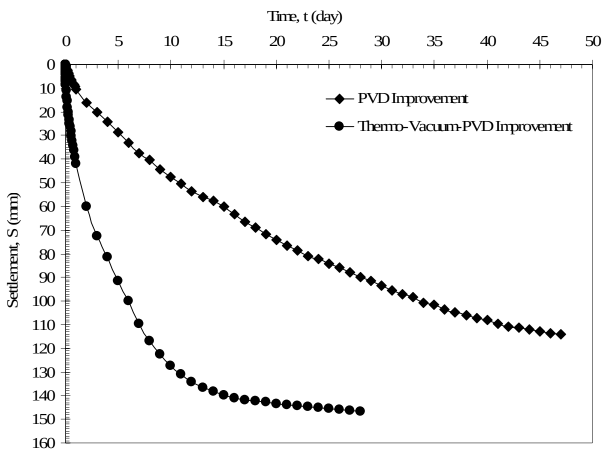


Fig. 4 Comparison of settlement of PVD improved reconstituted specimens with and without vacuum and heat

were measured by thermocouples which were embedded at 150mm depth and at radial distances of 25mm, 50mm 100mm and 200mm from the center of the specimen. The temperature variations with time in the Thermo-Vacuum-PVD specimens in the large consolidometer are plotted in Fig. 5. The temperature decreased with distance from the heat source. The radius, r, of 25 mm corresponded to the location of the smear zone with a mandrel dimension of 18.2 mm x 81.90 mm, and the diameter of the disturbed zone can be calculated as 87mm. The temperature of 80 ºC in the smear zone and decreased with distance from the heat source. It took 40 hours for the temperature to reach equilibrium in the large consolidometer. The result is consistency with the previous work of Abuel-Naga et al. (2006) where the temperature around the PVD decreased as the radial distance from the PVD increased.

Vacuum and Thermal Effect on Water Content

The reduction in water content was measured before and after consolidation tests at the radial distances of 25mm, 50mm, 100mm and 200mm from the center of the specimens at depths 10 mm and 40 mm. Lower water contents were observed nearer to the heat source with significant reduction in water contents. The levels of water content reduction decreased with the distance from the heat source. Fig. 6 shows the comparison of percent decrease in water contents before and after consolidation tests at radial distances of 25mm, 50mm, 100mm and 200mm from the center of the specimen. The percent decrease of water contents after consolidation tests at the smear zone of Thermo-Vacuum-PVD was slightly higher than that PVD only.

Effect of Vacuum and Heat on Shear Strength of Clay

A comparison of the increase in the shear strength at redial in all the four tests after improvement in the reconstituted specimens is plotted in Fig. 7. For the smear zone, the PVD was not much different in the increase of shear strengths. For Thermo-Vacuum-PVD, the shear strength had increased especially around the smear zone. The results demonstrated that much higher shear strength developed in the smear zone using Thermo-Vacuum-PVD. Similar to Abuel-Naga et al. (2006) shown that thermo-mechanical consolidation refers to the simultaneous increase of soil temperature and effective stress. The clay particle leads to flocculated structure as the soil porosity decreased due to increase temperature so that the thermal conductivity increased (Abuel-Naga et al. 2008).

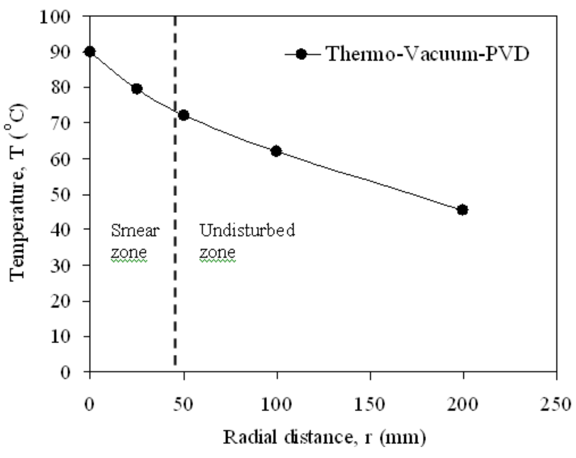


Fig. 5 Heat transfer at radial distances of PVD improved specimen with Thermo-Vacuum-PVD

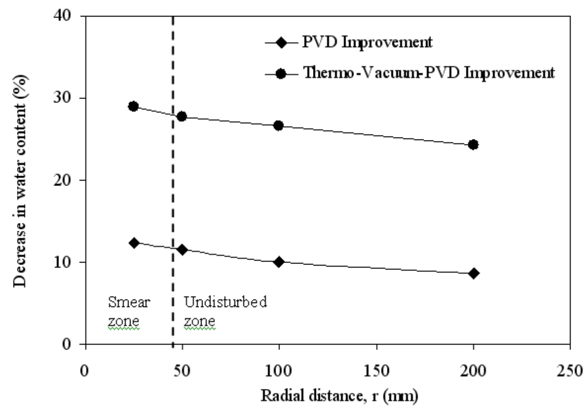


Fig. 6 Comparison of decrease in water content at radial distances of PVD improved reconstituted specimens with and without vacuum and heat

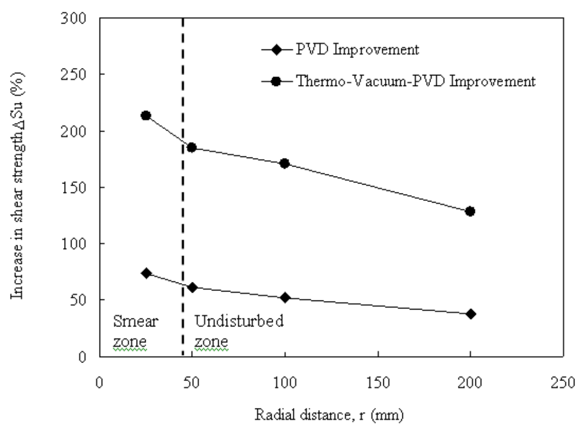


Fig. 7 Comparison of increase in shear strength at radial distances of PVD improved reconstituted specimens with and without vacuum and heat

Vacuum and Thermal Effects on Excess Pore Pressure

The excess pore pressures were measured at the large scale consolidometer tests during consolidation by using excess pore pressure transducers which were inserted through the wall of the cylinder cell into the smeared and undisturbed zone and monitored by digital data logger. The measured data are plotted in Fig. 8. For specimen improved with PVD, the excess pore pressure had increased to maximum of 80 kPa and decreased to about 10 kPa after 47 days in the undisturbed zone. The excess pore pressure of Thermo-Vacuum-PVD specimen in the undisturbed zone increased to 40 kPa and reduced very fast to -9.1 kPa after only 6 days and then decreased to about -43 kPa after 28 days. This behavior was reported by Indraratna et al. (2005) that the vacuum preloading generates negative (suction) excess pore pressure equivalent to the applied vacuum pressure. The thermally induced excess pore pressure and volume change because the thermal expansion coefficient of the pore water is approximately 15 times larger than the

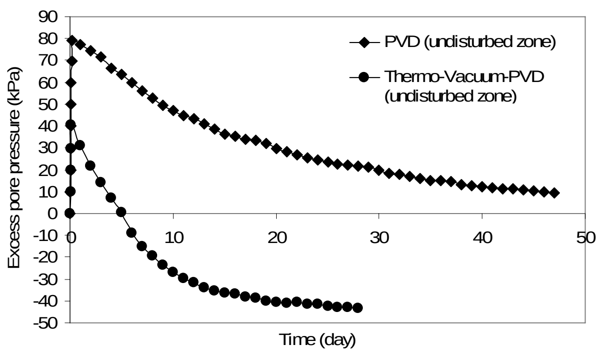


Fig. 8 Comparison of excess pore pressure of PVD improved reconstituted specimens with and without vacuum and heat

thermal expansion of the clay solid skeleton (Abuel-Naga et al. 2007).

C_h and k_h/k_s Values

The test results from reconstituted specimens in the new large scale consolidometer are back-calculated to determine the values of C_h and k_h/k_s by using the method from Hansbo (1987). The back-calculated values of reconstituted specimen improved with PVD is shown in Fig. 9, where C_h value is 1.93 m^2/yr with k_h/k_s of 3.0. Fig. 10 shows the results of reconstituted specimen improved with Thermo-Vacuum-PVD, the C_h and k_h/k_s are 4.38 m^2/yr and 1.1. The predicted curve agreed well with the observed values of reconstituted specimens in large scale consolidometer tests. The percent increases in C_h of the reconstituted specimen improved with Thermo-Vacuum PVD consisted of 126.42% with the reductions in k_h/k_s was 63.33%. Moreover, the increase in horizontal hydraulic conductivity in the smear zone of Thermo-Vacuum-PVD is 6.19 times or 518.94% of the horizontal hydraulic conductivity in the smear zone with PVD only.

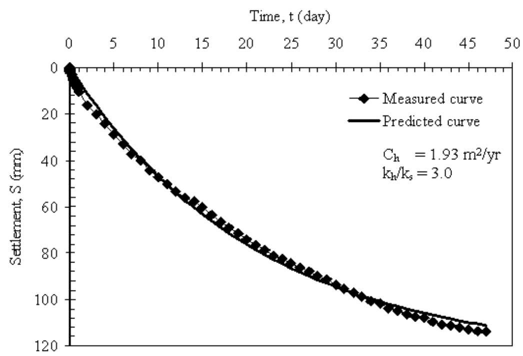


Fig. 9 The measured and predicted curves for settlements to determine C_h values for the reconstituted specimen improved with PVD

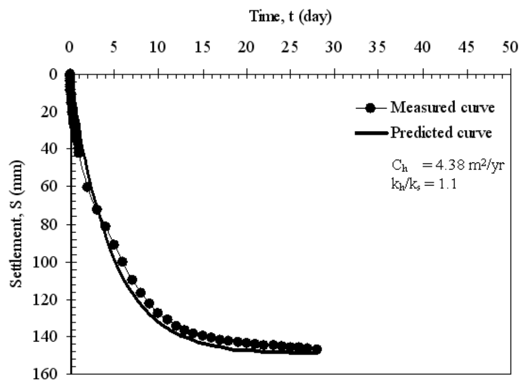


Fig. 10 The measured and predicted curves for settlements to determine C_h values for the reconstituted specimen improved with Thermo-Vacuum-PVD

Table 3 Flow parameters for specimens in large scale consolidometer

Flow parameters	PVD	Thermo-Vacuum-PVD
C_h (m^2/yr)	1.93	4.38
k_h/k_s	3.00	1.10

Table 4 Comparison of C_h and k_h/k_s values in percent compared to specimen improved with PVD in large scale consolidometer

Item	Thermo-Vacuum-PVD
Increase in C_h (%)	126.42
Decrease in k_h/k_s (%)	63.33
Increase in k_s (%)	518.94

Comparison of C_h, k_h/k_s and k_s values in percent compared to PVD improved specimens without and with vacuum and heat in large scale consolidometer of the reconstituted specimens are tabulated in Table 3 and 4, respectively.

Thus, the vacuum pressure can increase the horizontal coefficient of consolidation, C_h because applying vacuum pressure generates negative pore water pressure along the drain so the effective stress of soil increased which resulted in faster rate of settlement in the same magnitudes of settlement compared to PVD only. While, the high temperature can increase the coefficient of horizontal consolidation, C_h with the reduction of k_h/k_s that means permeability increased by reducing the drainage retardation effects in the smear zone around the PVD. Moreover, the soil elements also changed the volume of particle arrangement from the thermal effect which much faster rates of consolidation and higher magnitudes of settlement.

CONCLUSIONS

Base on the analyses and results of this study, the following conclusions can be made:

1. The PVD had lower settlement rate and less final settlement than Thermo-Vacuum-PVD.
2. The reduction of water content occurred with the increase in temperature and vacuum pressure around the PVD core.
3. The highest increase in shear strength was achieved in the smear zone and decreased with increasing radial distances from the PVD. Thermo-Vacuum-PVD improvement yielded high increase in shear strengths.
4. The excess pore pressures reduced faster in the smear zone than the undisturbed zone as expected and it decreased with the time. For the Thermo-Vacuum-PVD, the excess pore pressures reduced faster than the PVD due to the vacuum and heat increase in the hydraulic conductivity and decrease the viscosity of pore water due to high temperature.
5. The C_h and k_h/k_s values for reconstituted specimen in large consolidometer with PVD were 1.93 m^2/yr and 3, respectively. Meanwhile, the corresponding values were 4.38 m^2/yr and 1.1 for Thermo-Vacuum-PVD. The permeability of the smear zone increased due largely to heat and vacuum pressure effects.
6. The high temperature can increase the coefficient of horizontal consolidation, C_h with the reduction of k_h/k_s by the consequent increase in hydraulic conductivity and subsequently reduced the drainage retardation effects in the smear zone around the PVD.

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