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Improvement of Consolidation Characteristics around PVD Using the Thermal Method

열적 방법을 이용한 연직배수재 주변의 압밀특성 연구

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Abstract

This paper is to investigate the removal of the smear at elevated temperatures. This study utilized both small cylinder cell and large consolidometer apparatus to investigate the combination of PVD with heat and without heat. Two types of heaters are used in this study. The heater drain made of copper tube is used for all tests except large consolidometer and flexible wire heater is used for large consolidometer. Specimens demonstrated volume contraction upon heat and without heat. This contraction is dependent on temperature magnitude. When the specimen is heated, the magnitude of settlements is higher and rate of consolidation is faster. After treatment using PVD combined without heat and with heat for undisturbed specimens the C_h values obtained were 3.45m^2/yr and 3.83m^2/yr, respectively, from 3.2m^2/yr before treatment. The K_h/K_s ratios were 3 for the specimen without heat and 2 for the specimen with heat. Similarly, in reconstituted specimens without heat and with heat, the C_h values were 2.1m^2/yr and 2.5m^2/yr with K_h/K_s ratios of 1.75 and 1.5, respectively.

요 지

본 논문에서는 자체 제작한 연직배수재 내부의 열전대 설치 유무에 따라 소형 원형셀과 대형 압밀실험장치를 이용하여 배수재 주변의 압밀 정도를 평가하였다. 동판재료인 열전대로 제작한 연직배수재는 소형 원형셀 장치에 적용하였고, 대형 압밀실험장치에는 연성 와이어로 만든 열전대를 배수재 내부에 설치하여 실험을 각각 수행하였다. 실험결과, 흙 시료는 열의 영향으로 체적 수축이 발생하여, 열을 가하면 침하가 커지고 압밀속도는 더 빠르게 진행되었다. 특히, 불교란 시료의 경우, 배수재 내부에 열을 가하지 않았을 때와 가했을 때의 압밀계수 C_h는 각각 3.45와 3.83 m^2/yr, K_h/K_s 의 비는 각각 3과 2를 나타내었다. 또한 재성형 시료의 경우, 열을 가하지 않았을 때와 가했을 때의 압밀계수 C_h는 각각 2.1과 2.5 m^2/yr, K_h/K_s 의 비는 각각 1.75와 1.5를 나타내었다.

Keywords : Coefficient of consolidation, Heater drain, Thermal method, Undisturbed specimen

1. Introduction

The soft Bangkok clay in the Chao Phraya Plain extends to 200 to 250km in the East-West direction and 250 to 300km in the North-South direction. The thickness of soft to medium stiff clay in the upper layer varies from

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12 to 20m. Thick deposits of soft clay can consolidate and cause large settlements when loaded.

Loading may result directly from engineering structures or due to an increase in the effective stress caused by piezometric drawdown due to excessive extraction of groundwater causing ground subsidence. Associated with the low strength and high compressibility of the clay subsoils are the problems of low bearing capacity and unstable embankment and excavation slopes. Because of the low permeability of clay, primary consolidation settlement takes a long time to achieve. Prefabricated Vertical Drains (PVD) and preloading are very effective and economical ground improvement techniques for accelerating primary consolidation (Hansbo, 1979). However, the installation of prefabricated vertical drains using a mandrel causes disturbances of clay surrounding the drain, resulting in a "smear" zone with much lower horizontal permeability (Bergado et al., 1991; Sharma and Xiao, 2000). The presence of a smear zone significantly reduces the rate of horizontal consolidation time. From previous investigations, the permeability of the smear zone is reduced by as much as 2 to 6 times (Hird and Moseley, 2000).

Moreover, previous research on soft Bangkok clay shows that raising the clay temperature up to 90 degree centigrade increases its permeability about 3 to 4 times (Bergado et al., 2004). The aim of this study is to investigate the applicability of using the thermal effect up to 90°C combining with PVD as ground improvement technique and removal of the smear zone by thermal method.

2. Materials and Methods

The soil samples used in this study were obtained from a site which is located at the north of the Energy Park in the Asian Institute of Technology campus. The soft clay samples were collected from a depth of 3 to 4m. The mineralogical composition of soft Bangkok clay consists of smectite (montmorillonite and illite) ranging from 54 to 71% with kaolinite (28 to 36%) and mica. The liquid limit and plasticity index is 103% and 60%, respectively, and the natural water content is 80%. Both reconstituted and undisturbed clay samples are used.

The reconstituted samples were tested in small consolidometer and large consolidometer. The small consolidometer is composed of loading system and cylinder cell with 300mm in diameter and 300mm in height as shown in Fig. 1(a). The large consolidometer, shown in Fig. 1(b), is made of 10mm thick transparent PVC sheet 950mm height with an inner diameter of 450mm placed over a steel base plate. Geotextile will be placed on top of the soil to prevent clogging of the loading piston. Vertical load will be applied through a loading piston placed on top of the soil by using 19 rubber balloons connected to a compressor through a special regulator valve. The loading piston has 1 shaft arranged in the center to facilitate PVD-heater installation. Dial gauge will be placed on top

(a) Small consolidometer (b) Large consolidometer (c) Large oedometer

Fig. 1. Experimental Apparatus

of the shaft for settlement measurement. A lid placed on top of the PVC tube and tightened by 8 screws holds the apparatus in place. Steel rings will be wrapped around the cylinder to prevent bulging. There will be only one type of PVD installation as heater-PVD combination.

The undisturbed samples were tested in the small consolidometer and large oedometer apparatus. The small consolidometer is the same as the one used for the reconstituted samples. The large oedometer cell is made of 5mm thick steel 100mm height with an inner diameter of 200mm. The mechanism of the system for large oedometer is similar to that of convention oedometer test as shown in Fig. 1(c).

Two types of heaters, U-shaped duct heater and flexible wire heater, were used. The former heater is made of copper tube with 10mm in diameter and it was bent to U-shape 30mm wide and 300mm long. For all tests, there were 2 types of installation such as PVD without heat and PVD with heat. The first sample has only one PVD in the middle of the sample and the second sample has one heater-PVD in the middle of the sample. The hot water will be circulated along the duct provided adjacent to the PVD. The schematic diagram of heating system with U-shape duct heater is shown in Fig. 2. The flexible wire heater is used for large consolidometer.

For the reconstituted specimen in small consolidometer, the load was increased to 20kPa after reconstitution under

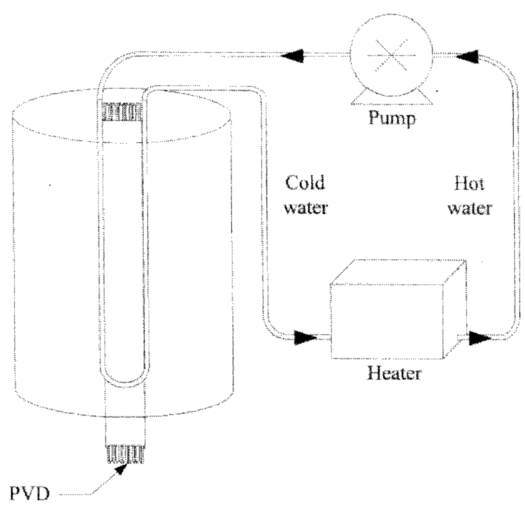


Fig. 2. Schematic diagram of the laboratory in thermal stabilization by water

the 10kPa pressure in the specimen without heat. The temperature in specimen using PVD combining with heat was elevated up to 90°C together with pressure increment. In large consolidometer, silicon grease was applied to the insides of the cylinder to reduce friction. The soil sample was consolidated at 50kPa applied vertical pressure. The increasing of temperature up to 90°C by heater was started after 90% degree of consolidation settlement.

For the undisturbed specimen in the small consolidometer, the soil specimens were consolidated under 30kPa vertical pressures. In large oedometer test, the soil specimens were consolidated under 100kPa and load is applied in three steps of 25kPa, 50kPa and 100kPa. At the same time as loading, the temperature was increased up to 90°C for the specimen with heat in both cases.

Initial water content and shear strength were determined before consolidation. After treatment, water content and shear strength were measured at three locations across the drains, namely: 25mm, 50mm and 100mm away from heating point for both undisturbed samples and reconstituted samples.

3. Discussions of Test Results

3.1 Consolidation Settlements

For the reconstituted specimens in small consolidometer, two tests were conducted on this study. Specimens were firstly consolidated with 10kPa under room temperature until 90% degree of consolidation. Afterwards the vertical load was increased up to 20kPa under temperature 25°C and 90°C for testing PVD without heat and with heat, respectively. The comparison of PVD without heat and with heat is shown in Fig. 3. The PVD with heat registered faster rate of settlements. For large consolidometer the testing method is the same as in the small cylinder cell as mentioned previously. However, the applied vertical pressure is 50kPa instead of 20kPa. The initial height of the sample after reconstitution was 600mm. The effect of increasing temperature up to 65°C on the settlement of the sample is shown in Fig. 4. Similarly, the application of heat with PVD increased the rate of consolidation.

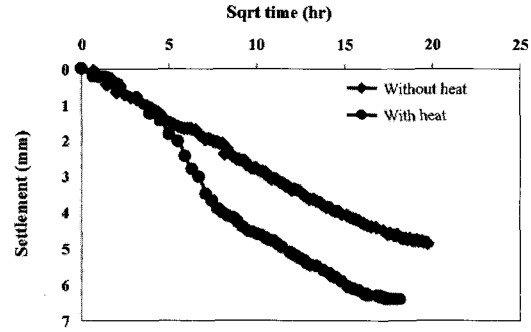


Fig. 3. Comparison of consolidation curves with and without heat in small consolidometer with reconstituted specimens

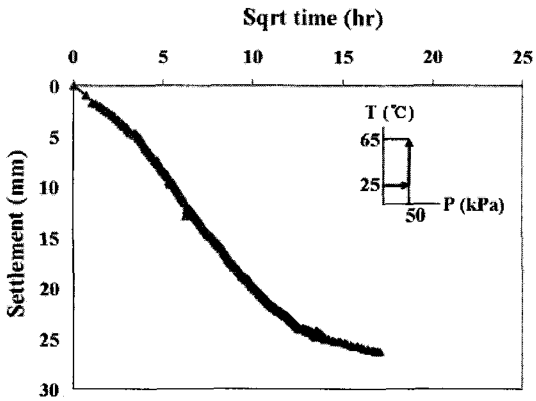


Fig. 4. Consolidation curve under 50kPa pressure of reconstituted specimen in large consolidometer

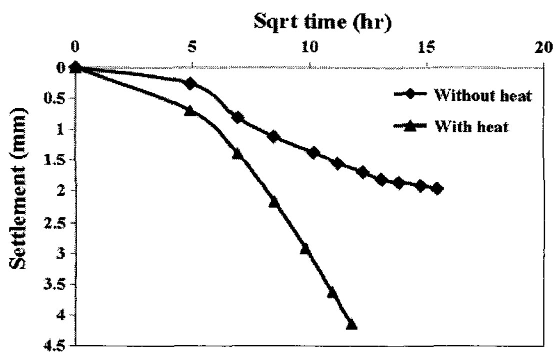


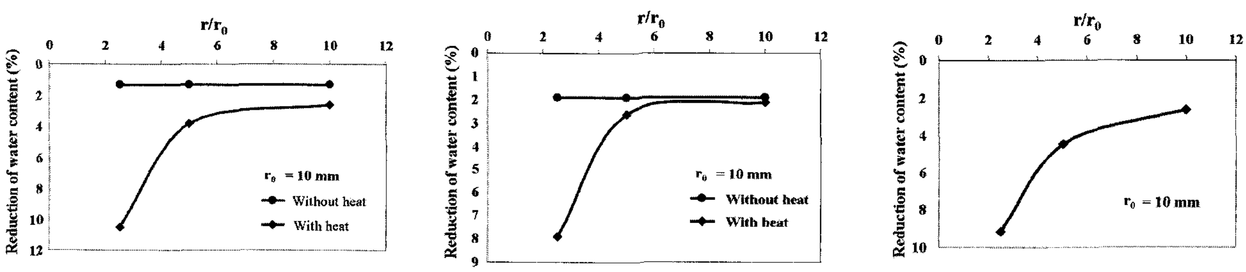
Fig. 5. Comparison of consolidation curves with and without heat in undisturbed specimens under 30kPa pressure

For small cylinder cell, the undisturbed specimens were consolidated under 30kPa with and without heat. The results indicate that heating the specimen resulted in volume contraction and also increased rate of consolidation. The comparison of PVD without heat and with heat is shown in Fig. 5. From the consolidation settlements of the tests with and without heat, it is clear that higher volume contraction and faster rate of consolidation settlement occurred due to heat application.

3.2 Physical Properties

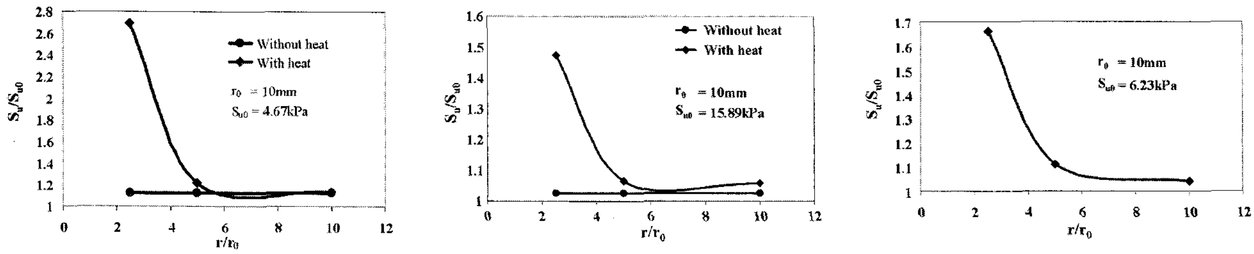
The reduction of water content was measured around the heat source at the position, namely: 2.5, 5, 10 times the radius of heater (r_0 = 10mm) using both undisturbed and reconstituted specimens.

For consolidation test with reconstituted specimens in small cylinder cell, the initial water content after reconstitution was observed as uniform with 92.6% for the whole samples. By increasing the temperature up to 90°C under constant pressure, the reduction of water contents of reconstituted samples measured at distance 25, 50, and 100mm away from the heat source in the test without heat is 1.3% for all points due to drainage with PVD while for test with heat, the corresponding values are 10.5%, 3.4%, and 2.6%. High reduction of water content is observed around heat source and is slightly reduced with distance from the heating points. The reductions of water contents of all samples are plotted in Fig. 6. When the drain was installed, it shortened the drainage path of the pore water pressure in the soil. Instead of traveling in the vertical direction, the water now flows in the horizontal



(a) Reconstituted specimens in small consolidometer
(b) Undisturbed specimens in small consolidometer
(c) Reconstituted specimens in large consolidometer

Fig. 6. Variation of reduction of water content after consolidation (90°C)



(a) Reconstituted specimens in small consolidometer

(b) Undisturbed specimens in small consolidometer

(c) Reconstituted specimens in large consolidometer

Fig. 7. Normalized undrained shear strength after consolidation (90°C)

direction towards the PVD since the drains created a shorter path for the water to follow causing moisture reduction on the clay.

Vane shear strength, S_{u0} of 4.67kPa was initially measured after reconstitution by using the customized vane shear apparatus at the same testing positions as the water content measurements. After consolidation, the variations of shear strength around the heat source of reconstituted samples in small cylinder cell are shown in Fig. 7(a), for the tests with and without heat. The figure reveals significant strength increases on heated sample about 168%, 34%, 26% at distance 25, 50, 100mm from the heat source, respectively, compared to the shear strength of unheated sample. Thus, the shear strength increased due to heating. Figs. 7(b) and (c) show the results for undisturbed specimens and reconstituted specimens in large consolidomerter which show the increase in shear strength due to application of heat.

3.3 Coefficient of Consolidation

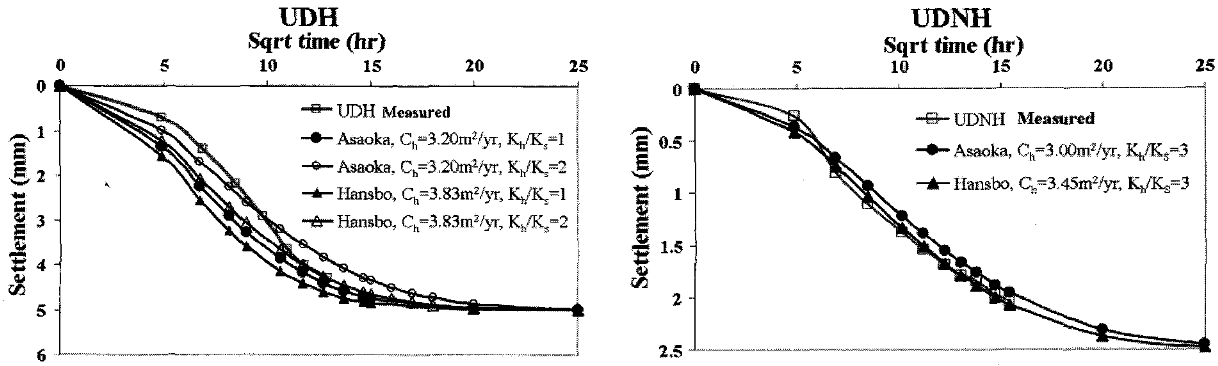
The coefficients of consolidations of samples were tested for reconstituted and undisturbed samples from small cylinder cells before consolidation. The value of C_v for undisturbed sample examined from conventional oedoemter test is 1.6m^2/yr for 30kPa. From the results of Asakami (1988), the ratio of C_h/C_v is around 2.0. Thus, the obtained C_h value is 3.2m^2/yr. Nayar (1996) has shown that the ratio of the C_h/C_v was 2.10. The C_v value for reconstituted sample obtained from oedometer test is 1.02m^2/yr so that the C_h value can be 2.04.

After treatment using PVD with heat and without heat, the horizontal coefficient of consolidation is back-calculated by the methods of Asaoka (1978) and Hansbo (1987). Asakami (1988) found that the value of K_h/K_s ratio is around 3 and 1.75 for undisturbed and reconstituted samples, respectively.

Figures 8(a) and (b) show the measured and back-calculated C_h values of heated and not-heated undisturbed specimens by using both methods of Asaoka (1978) and Hansbo (1987) for various K_h/K_s values. The C_h values 3.45 and 3.83m^2/yr from Hansbo's method for K_h/K_s values 3 and 2 are in agreement with the observed values for not heated and heated specimens, respectively. For undisturbed specimens, the C_h values increased and the K_h/K_s decreased due to the increase in the coefficient of permeability due to heat application.

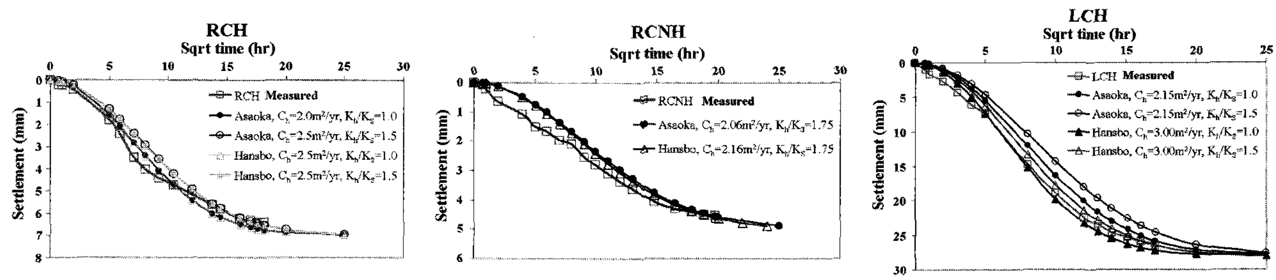
Similarly, for reconstituted samples, Figs 9(a) and (b) show the measured and back-calculated C_h values using both Asaoka (1978) and Hansbo (1987) methods. The C_h equals 2.06m^2/yr to 2.16m^2/yr were found in the sample without heat for K_h/K_s equals 1.75. In the sample with heat, obtained C_h value was 2.5 for K_h/K_s equals 1.5. In the test for large consolidometer with heat, C_h value is observed as 2.15 to 3 for K_h/K_s equals 1.0, as shown in Fig. 9(c). For reconstituted specimens, the C_h values are lower compared to the undisturbed specimens. In the same manner, the C_h values increased while the K_h/K_s values decreased due to the increase of the coefficient of permeability due to heat application.

For reconstituted specimen in large consolidometer with heat, the back-calculated C_h values were from 2.15 to 3.0m^2/yr using K_h/K_s of 1.0 to 1.5. The value of C_h equals 3m^2/yr at K_h/K_s equals 1.5 obtained from Hansbo (1987) method



(a) Small consolidometer with heat (b) Small consolidometer without heat

Fig. 8. The observed and trial curves for settlements to predict C_h values for undisturbed specimen



(a) Small consolidometer without heat (b) Small consolidometer with heat (c) Large consolidometer with heat

Fig. 9. The observed and trial curves for settlements to predict C_h values for reconstituted specimen

Table 1. Comparison of C_h and K_h/K_s values for not heated and heated specimens

	Undisturbed	Specimens	Reconstituted	Specimens
	Without heat	With heat	Without heat	With heat
C_h (m^2/yr)	3.45	3.83	2.1	2.5
K_h/K_s	3.0	2.0	1.75	1.5

were closer to the observed values. Table 1 tabulated the summary of the measured and back-calculated results.

4. Conclusions

The studies described in proceeding pages have demonstrated the observed effects of elevated temperatures on the consolidation behavior of clays. Laboratory testing programs were conducted for undisturbed and reconstituted samples in small cylinder cells, large consolidometer and large oedometer cell to measure the effectiveness of thermal treatment. All samples are from depths of 3 to 4 m. From the results of the tests, the following conclusions can be drawn:

Specimens demonstrate consolidation settlement with and without heat. This contraction is dependent on temperature magnitude. When the specimens are heated, faster rates of consolidation and larger settlements were achieved. Reduction of water content occurred with the increase in temperature. High reduction of water content was achieved around heat source, within 2.5 times the radius of heat source, i.e, 2 times of the diameter of the smear zone, while at farther distances the water content reduces slightly.

Shear strength increases with increasing temperature and decreasing water content. Moreover, high increase in shear strengths were achieved within the same limited zone at distance 2 times the radius of heater away from heat source, i.e, 2 times of the diameter of the smear zone. The C_h and K_h/K_s values for undisturbed specimens without heat were 3.45m^2/yr and 3, respectively. Upon subjecting to heat the corresponding values were 3.83m^2/yr and 2. The testing period for undisturbed specimen without heat is 10 days and the specimen with heat is 6 days. The C_h and K_h/K_s values for reconstituted specimens without heat were 2.1m^2/yr and 1.75, respectively. Upon subjecting to heat the corresponding values were 2.5m^2/yr and 1.5. The testing period for reconstituted specimen without heat is 16 days and the specimen with heat is 13 days.

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