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Enhancement of PVD Performance by Thermal and Electro-Osmotic Techniques

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ABSTRACT

This paper examines the innovative techniques for enhancing the performance of the prefabricated vertical drain (PVD) consisting of thermal and electro-osmotic consolidation techniques. The electro-osmotic consolidation of soft Bangkok clay was first studied. Laboratory testing program were done on undisturbed and reconstituted sample in large consolidometer under voltage gradient of 60 and 120 V/m with 24 hours polarity reversal. The time to achieve 90% degree of consolidation induced by electro-osmosis ranged from 1.4 to 2.1 and 2.1 to 2.2 times faster than the normal consolidation with PVD only, for undisturbed and reconstituted samples, respectively. Faster rate of consolidation and higher magnitudes of settlement were achieved at higher voltage gradient. Subsequently, the performances of thermo-PVD which involves increasing simultaneously both the vertical effective stress and the surrounding clay temperature up to 90°C were investigated using the large consolidometer. The test results demonstrated that higher consolidation rates were observed for the clay specimen at elevated temperatures for both undisturbed and reconstituted specimens. This behavior can be attributed to the increase in the clay permeability with temperature. Therefore, raising the clay temperature can enhance the performance of PVD by reducing the drainage retardation at the smear zone around the PVD.

Key words: soft clay, PVD, thermal, electro-osmotic

INTRODUCTION

Prefabricated Vertical Drains (PVD) is a very effective and economical ground improvement technique for accelerating primary consolidation and compensating some secondary compression of soft compressible soils. However, the installation of prefabricated vertical drains using a mandrel causes disturbance of clay surrounding the drain, resulting in a smear zone of much lower horizontal permeability of the clay. The presence of a smear zone significantly influences the horizontal consolidation resulting in retardation of the overall consolidation rate. The long duration required to accomplish the ground improvement using PVD is the disadvantage of this technique.

An intensive experimental study has been conducted to investigate the thermo-mechanical behavior of soft Bangkok clay. The test results from oedometer test program, where the soil specimen temperature was raised up to 90°C under constant stress condition, show that the thermally induced volume change is stress history dependent

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(Abuel-Naga *et al.* 2005a and b). The normally consolidated clays contracted irreversibly and non-linearly upon heating whereas the highly overconsolidated clays exhibited reversible expansion. Moreover, an apparent overconsolidation state was observed after subjecting the normally consolidated specimen to heating/cooling cycle. The effect of temperature on hydraulic permeability of soft Bangkok clay was also investigated by Bergado *et al.* (2004). Flexible wall permeameter test program was conducted at different elevated temperatures up to 90°C. The results show that as the soil temperature increases, the permeability increases. This behavior was attributed to the thermal evolution of the pore soil liquid viscosity.

If in a compressible soil, electro-osmosis draws water to a cathode where it is drained away and no water is allowed to enter at the anode, then consolidation of the soil between the electrodes occurs in an amount equal to the volume of water removed. As water movement away from the anode causes consolidation in the vicinity of the anode, the effective stress must increase. Because the total stress in the vicinity of the anode remains essentially unchanged, the pore water pressure must decrease. On the other hand, there is no consolidation at the cathode since water flows towards it. It means that there is no change in total, effective and pore water pressures. As a result, there develops a hydraulic gradient that tends to push water back from cathode to anode. Consolidation continues until the hydraulic force that drives water back toward the anode exactly balances the electro-osmotic force driving water toward the cathode.

The pore water pressure developed due to electro-osmotic consolidation has been induced from the proportion of the electrically induced velocity of water flow through soil, v_e, the voltage gradient (electric field), $\partial V/\partial x$, and the coefficient of electrokinetic permeability, k_e. Assuming the validity of superposing electrically and hydraulically induced flows through an incompressible soil mass, the governing partial differential equation for electro-osmotic consolidation can be obtained.

MATERIALS AND METHODS

Thermo-mechanical consolidation with PVD

Large oedometer apparatus was utilized in this study where dead load was used to apply the required vertical stress as shown in Figure 1. The large oedometer cell can accommodate sample up to a height of 200 mm and diameter of 300 mm. Dial gauges were provided to monitor settlement during the consolidation process. The soil temperature was raised using either line heat source attached to PVD point (Thermo-PVD) or installed independently between the PVD points. The core was cut to 20 mm in width and about 200 mm in length. Thermo-PVD was created by using two scaled-down PVD cores fitted back to back where flexible wire heater (2 mm in diameter) was sandwich in the grooves between them as shown in Figure 2a. The separate line heat source was created by wrapping flexible wire heater around metal sheet with 20 mm wide and 200 mm long as shown in Figure 2b. For both type of line heat source, a thermocouple (K-type) was placed at the mid height of line heat source indirect contact with the surrounding soil. It was used for temperature measurements and the feedback signal for the thermo-controller unit.

Reconstituted soft Bangkok clay specimens obtained from 3.0 to 4.0 m depth were used in this study. 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%. The reconstituted samples were prepared by applying a consolidation pressure of 10 kPa to the remolded sample. The remolded sample was

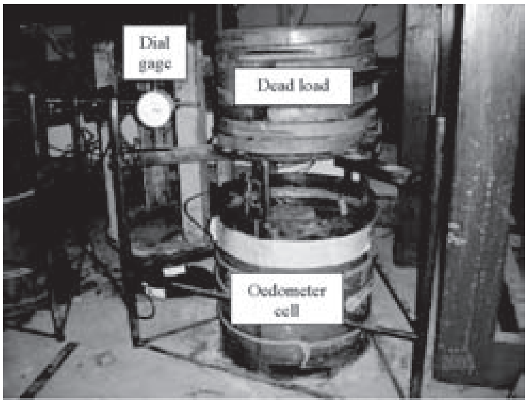
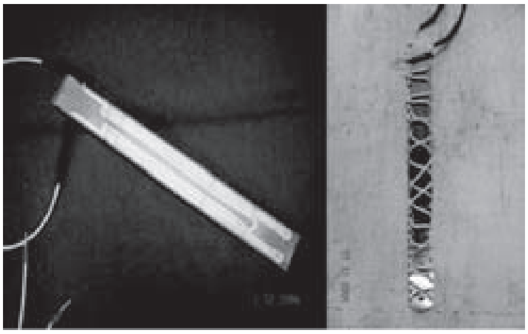


Figure 1 Large oedometer apparatus.



(a) (b)

Figure 2 a) Thermo-PVD configuration; b) Line heat source configuration.

obtained by adding a sufficient amount of water until its water content was about 1.2 times of its liquid limit.

The objective of this study is to investigate the heat transfer behavior around line heat source and thermo-mechanical consolidation behavior of soft Bangkok clay using line heat source and PVD. The heat transfer study involves measurement of soil temperature change at different distances from the thermo-PVD point of 90°C constant temperature. Thermo-couples were inserted at the mid height of the soil specimen (100 mm) with different r/r_e ratios (1.0, 3.34, 8.34, 16.67) where r and r_e are the distances between the thermo-couple and the center of the thermo-PVD, and equivalent radius of thermo-PVD (r_e=6 mm), respectively. Reconstituted specimen at 10 kPa was used in this study.

The thermo-mechanical consolidation study involves raising simultaneously both of the line heat source point temperature (from 25°C to 90°C) and the vertical effective stress (from 10 to 20 kPa) and measuring the volume change. Two tests were conducted in this study as shown in Figure 3.

Electro-osmotic consolidation with PVD

Electro-osmotic consolidation was performed by using a large oedometer. The schematic diagram of this experimental apparatus is depicted in Figure 4. Similar to the apparatus used by Abiera *et al*. (1999), the large oedometer consisted of loading piston located on the top of the frame where air pressure was being supplied by a compressor and was adjusted properly by a valve regulator. The large oedometer cell can

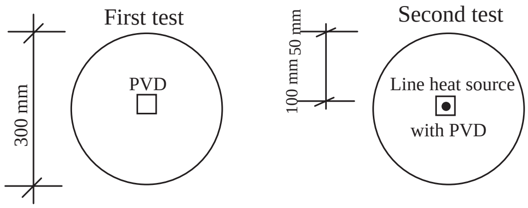


Figure 3 Thermo-mechanical consolidation test configurations.

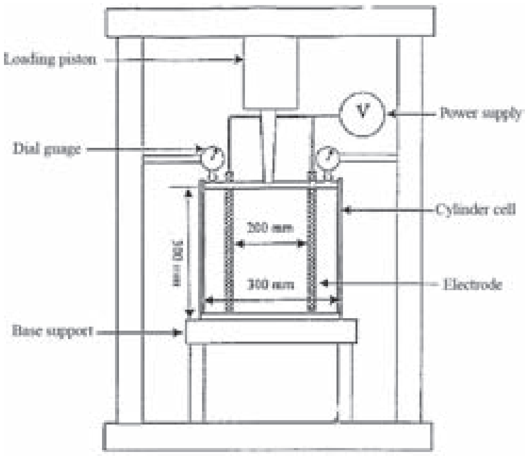


Figure 4 Large oedometer electro-osmotic cell.

accommodate a sample up to 300 mm in diameter and 300 mm in height. Two holes, 200 mm apart, at the top and bottom were provided for PVD installation (see Figure 5). Undisturbed and reconstituted sample were tested in this apparatus.

In this investigation, the direct measurement of pore pressure distribution was not done, since the paper concentrates mainly on settlement change with time, and physical and chemical improvement due to preloading and electro-osmosis. Additional details of this apparatus are given by Bergado *et al.* (2000).

The soft Bangkok clay used in this study was obtained from a site in the Asian Institute of Technology campus at the depth of 3 to 4 m. The reconstituted sample was prepared by applying consolidation pressure to remolded sample. A reconstitution pressure of 5 kPa was used for the large oedometer. All reconstituted sample were loaded until 90% consolidation was achieved using Asaoka's method (Asaoka, 1978). The undisturbed samples were taken by extruding them from a 254 mm diameter piston sampler. The degree of saturation was higher than 97% for all test specimens. Hence, both the undisturbed and reconstituted samples were considered to be saturated.

The adjusted size of PVD with electrode is 20 mm wide with the 300 mm for the large oedometer. The copper and carbon electrodes were made by inserting 8 copper rods 13.6 mm in diameter and 8 carbon fibers, respectively into the grooves of the drain core (4 on each side) and covering by a filter. This combination of PVD with electrode was inserted into the soil sample together with another drain without electrodes for drainage purposes. Both anode and cathode are allowed to drain since there are two directions of drainage: towards the anode due to the applied vertical load and towards the cathode due to the eletro-osmosis.

Electro-osmotic consolidation on large oedometer was conducted under the vertical pressure of 5 kPa with 24 hours polarity reversal. Polarity reversal was carried out every 24 hours so as to obtain the uniform shear strength distribution along the sample (Lo *et al.,* 1991). Several tests were carried out on undisturbed and reconstituted samples using variable parameters namely: electrode type and voltage gradient as tabulated in Table 1. Since this investigation is the pioneering work on soft Bangkok clay, which mainly concentrated on the performance of the soil improved by PVD with electrodes and the applicability of this technique in the soft clay rather than the design aspect. Then, the voltage gradient is simply defined as the ratio of the applied voltage to spacing between anode and cathode, as has been termed by Abiera *et al.* (1999). The amounts of settlement, voltage, current and temperature were measured across the electrodes during the test at predetermined time. All tests were stopped once the 90% degree of consolidation was achieved using Asaoka's method.

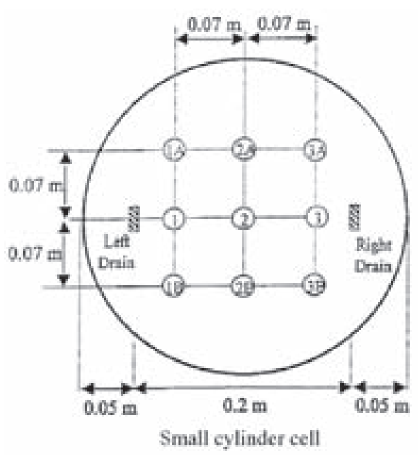


Figure 5 PVD locations and sampling points.

RESULTS AND DISCUSSIONS

Thermo-mechanical consolidation with PVD

The temperature-distance relationship at steady state condition is plotted in T/T_o-r/r_e plane as shown in Figure 6, where T and T_o are the measured and room temperature (25°C), respectively. The steady state condition was

Table 1 Summary of electro-osmotic tests conducted.

Test	Sample type	Voltage gradient (V/m)	Vertical pressure (kPa)	Polarity reversal Duration (hr)	Electrode type
A	Undisturbed	0	5	24	PVD only
B	Undisturbed	60	5	24	Copper
C	Undisturbed	60	5	24	Carbon
D	Undisturbed	120	5	24	Copper
E	Undisturbed	120	5	24	Carbon
F	Reconstituted	0	5	24	PVD only
G	Reconstituted	60	5	24	Copper
H	Reconstituted	60	5	24	Carbon
I	Reconstituted	120	5	24	Copper
J	Reconstituted	120	5	24	Carbon

achieved after 10 hr from the beginning of the test. The test results indicate that the temperature change around Thermo-PVD decreases as the radial distance increases and becomes constant in the zone defined as $r/r_e \geq 8.0$. Figure 7 shows the comparison between the consolidation behavior of the reference test conducted at room temperature and the thermo-mechanical test where the soil temperature and the vertical stress were increased simultaneously. The final settlement of the thermo-mechanical test is higher than the reference test. This difference in the final settlement can be attributed to the thermal consolidation effect. However, the results also show that the consolidation rate of the thermo-mechanical test is higher than the reference test. The final settlement of the reference test occurred after 360 hours while the same value of the settlement can be obtained after only 120 hours using thermo-mechanical path. This behavior can be interpreted in the light of the increased of soil permeability as the temperature increased.

Electro-osmotic consolidation with PVD

The soil sample demonstrated the favorable response to electro-osmotically induced

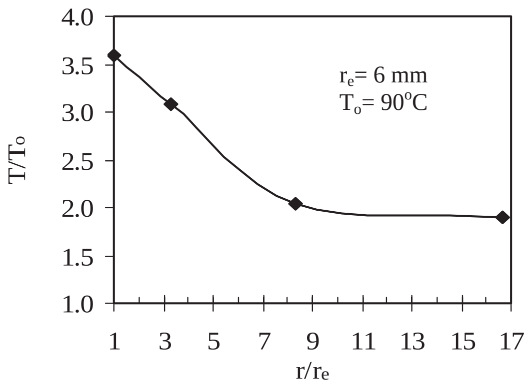


Figure 6 Temperature-distance relation at steady state condition around Thermo-PVD point.

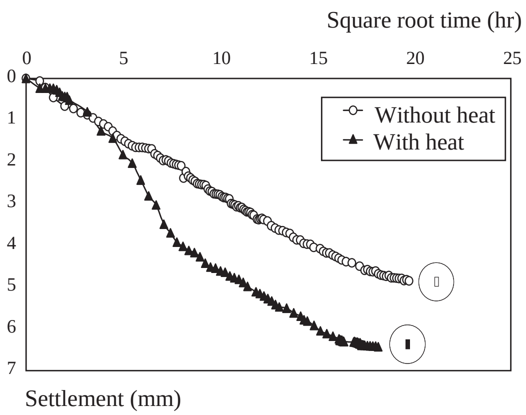


Figure 7 Comparison of consolidation curves of reconstituted specimens in large oedometer.

consolidation after vertical load and electrical gradient had been applied. The discharge of water was observed at the cathode for about 72 hours of the treatment time. In the sample using copper electrode, the water discharge was greenish in color whereas it was dark brown in case of carbon electrode due to the corrosion of copper and disintegration of carbon electrode, respectively. The shapes of settlement vs time curves are similar for both consolidation with PVD only and electro-osmotic consolidation as shown in Figure 8 for reconstituted sample. To achieve 90% degree of consolidation induced by electro-osmosis, the time periods range from 1.2 to 2.2 times faster than using PVD only for reconstituted samples in large oedometer cell. The carbon electrode achieved more settlement and faster rate of consolidation. Highly corrosive effect on the copper electrode was observed due to the oxidation reaction. It was clear that carbon electrodes generated faster rate of consolidation and achieved greater settlement at the same vertical load and voltage gradient before its efficiency was hindered by its disintegration.

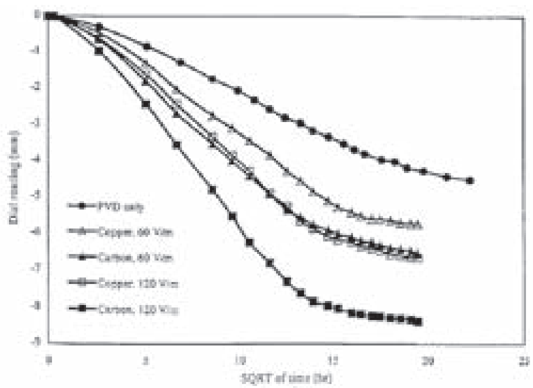


Figure 8 Settlements versus time curves.

CONCLUSIONS

Based on the test results of thermo-mechanical and Electro-osmetic consolidation conducted using large oedometer apparatus, the following points can be concluded:

1. The thermo-mechanical consolidation with PVD shows promising results. It enhanced the performance of preloading with PVD by reducing significantly the consolidation time by 2 to 3 times.

2. The retardation of consolidation at the smear zone could be reduced due to the increased permeability at elevated temperatures.

3. The soft Bangkok clay showed favorable response to electro-osmotic consolidation using the combination of electrodes with PVD.

4. The rate of electro-osmotic consolidation was achieved 1.2 to 2.2 times faster than using PVD only for reconstituted sample.

5. At higher voltage gradient, faster rate of consolidation and higher magnitude of settlements were achieved.

6. Although carbon electrodes decomposed with time due to acidic medium, it achieved faster rates of consolidation and more settlements than copper electrode. With polarity reversal, the carbon electrodes were beneficial to induce consolidation before its efficiency was hindered by its disintegration.

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