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Thermo-mechanical consolidation of soft Bangkok clay: innovative technique using PVD

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ABSTRACT: Previous research works in literature show that subjecting the saturated fine-grained soils to temperature less than water boiling point (100°C) induces volumetric and shear strength changes depend on the stress history. These alterations of the soil properties have been attributed to the thermo-physico-chemical changes at the microscopic level. Recently, intensive experimental program has been conducted to investigate the effect of temperature, up to 90°C, on the engineering properties of soft Bangkok clay. In the range of temperatures investigated, normally consolidated soft Bangkok clay exhibited irreversible contraction temperature induced volume change, stiffening, and increased hydraulic permeability with increasing temperature as well as apparent overconsolidation state after subjecting to heating/cooling cycle. These findings encourage further research towards employing the thermal load only, up to 90°C, or in combination with mechanical loading as ground improvement technique. This paper study the applicability of this technique through series of large oedometer tests conducted on reconstituted soft Bangkok clay specimens. Heating was conducted using flexible wire heater attached to the PVD point or separate line heat source. The tested specimens have been subjected to either thermal load or thermo-mechanical load. The test results show that the combination between the thermal load and the mechanical load gives promising results since it accelerates the rate of consolidation and increase the amount of total settlement.

1 INTRODUCTION

Construction of road embankment on top of soft deposits formation, which is mainly normally consolidated clays, required pre-consolidation and strengthen of the weak compressible soils. Prefabricated Vertical Drains (PVD) is a very effective and economical ground modification 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.

The aim of this study is to investigate the effect of soil temperature on the performance of pre-loading with PVD ground improvement method using large oedometer apparatus (300 mm in diameter). The experimental program was directed to study the pattern of heat transfer around line heat source, and thermal consolidation and thermo-mechanical consolidation behavior of soft Bangkok clay using line heat source and PVD with different arrangements. A brief back ground pertaining to the thermo-mechanical behaviour of saturated clays is presented in the following section. Later on, testing equipment, test specimen and experimental program are described in detail. Subsequently, the test results are presented and conclusions are drawn.

2 BACKGROUND

During the last three decades, the increased interest of radioactive disposal in deep clay formations gives more attention to understand the thermo-mechanical behaviour at temperatures up to 100°C. Extensive experimental work has been carried out on some European deep clays to investigate their response as a host geological formation for the radioactive waste disposal (Del Olmo et al. 1996). These studies have conclusively demonstrated that increasing the temperature of saturated fine-grained soils to less than the boiling point of water (100°C), affects the engineering behaviour of soils (permeability, compressibility, and shear strength). A comprehensive review of these aspects has been carried out by Laloui (2001).

An intensive experimental study has been conducted by Abuel-Naga (2005a) to investigate the thermo-hydro-mechanical behaviour 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 (Abuel-Naga et al. 2005b). 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 behaviour was attributed to the thermal evolution of the pore soil liquid viscosity.

Abuel-Naga et al. (2006) investigate experimentally the effect of temperature on the undrained triaxial compression shear strength behaviour of normally consolidated soft Bangkok clay specimens at different temperature levels and histories. Temperature history means that specimen was subjected to heating cooling cycle before shearing test. The test results indicated that the undrained shear strength and secant modulus of the normally consolidated clay increases as the soil temperature increases or after subjecting to a temperature history. These findings encourage the authors to investigate the potential of employing the PVD system with thermal load only or in combination with mechanical load as ground improvement technique.

3 EXPERIMENTAL STUDY

3.1 *Test Apparatus*

Large oedometer apparatus was utilized in this study where dead load was used to apply the required vertical stress as shown in Fig. 1. The large oedometer cell can accommodate sample up to a height of 200 mm and diameter of 300 mm. Dial gauge was 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. Figure 2 show different arrangements of PVD and line heat source that were investigated. The scaled-down of PVDs were created by disassembling, cutting, and reassembling the full-size drains. 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 Fig. 3a. 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 Fig. 3b. 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.

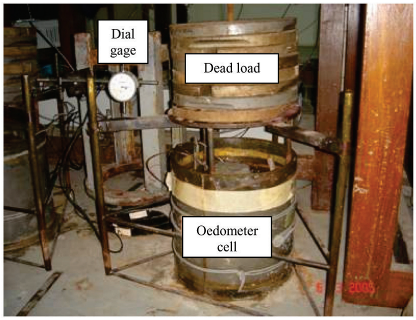

Figure 1. Large oedometer apparatus.

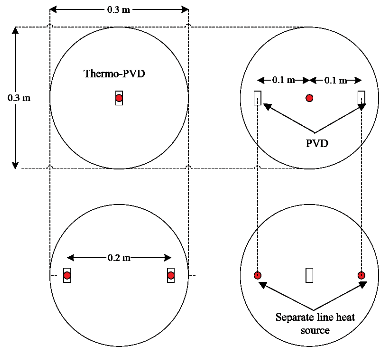

Figure 2. Different arrangements of Thermo-PVD, PVD, and line heat source heater spacing in large oedometer cell.

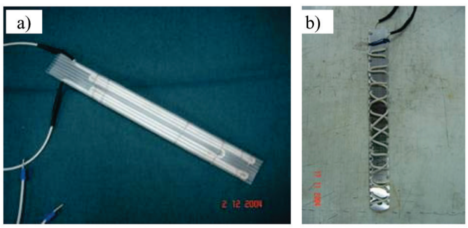

Figure 3. (a) Thermo-PVD configuration; (b) Line heat source configuration.

3.2 *Tested Specimen*

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.

The reconstituted sample was prepared by applying a consolidation pressure to the remolded sample. The remolded sample was obtained by adding a sufficient amount of water until its water content was about 1.2 times greater than its liquid limit. The reconstitution pressures of 10 kPa were used. All reconstituted samples were loaded until 90% consolidation was achieved.

3.3 *Large Oedometer Testing Program*

The objective of this study is to investigate the heat transfer behavior around line heat source, and thermal consolidation and thermo-mechanical consolidation behavior of soft Bangkok clay using line heat source and PVD with different arrangements.

The heat transfer study involves measurement of soil temperature change at different distanced from 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 distance 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 thermal consolidation study involves raising the temperature of Thermo-PVD or separate line heat source point up to 90°C, and measuring the thermally induced volume change under equal strain condition. Reconstituted normally consolidated specimens at 10 kPa were used in this study. Four tests were conducted with different Thermo-PVD, PVD, and separate line heat source arrangements as shown in Fig. 2.

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 under equal strain condition. Two tests were conducted in this study as shown in Fig. 4. The first test is considered as reference consolidation test where the thermal effect is not including. The specimen of the second test was provided by line heat source in the center in order to study the thermo-mechanical consolidation behavior.

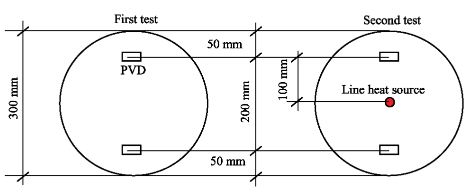

Figure 4. Thermo-mechanical consolidation test configurations.

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

The temperature-distance relationship at steady state condition is plotted in T/T_o – r/r_e plane as shown in Fig. 5, where T and T_o are the measured and room temperature (25°C), respectively. The steady state condition was 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 $r/r_e \geq 8.0$.

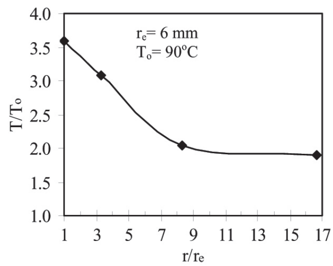

Figure 5. Temperature-distance relation at steady state condition around Thermo-PVD point.

The thermal consolidation test results of reconstituted normally consolidated soft Bangkok clay at 10 kPa vertical effective stress using different arrangements of PVD, and Thermo-PVD or line heat source (Fig. 2) were plotted in settlement-root square time plane as shown in Fig. 6. For the samples that contain one PVD point (Fig. 2a, d), the final thermally induced volume change was approximately equal to 4.0 mm. However, the sample with Thermo-PVD shows higher rate of consolidation. This behavior can be attributed to the expected difference in the thermally induced excess pore water pressure

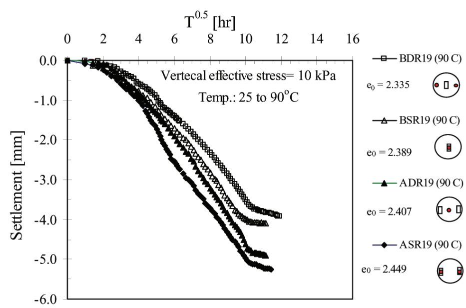

Figure 6. Thermal consolidation test results.

dissipation behavior. Similar behavior was observed for the samples that contain two PVD points (Fig. 2b, c); however, the final settlement of the thermally induced volume change was approximately equal to 5.0 mm. Based on these results, we can conclude that the volume change that generated by thermal consolidation path is very small and insignificant. The non-success of this path can be attributed to the low thermal conductivity of soil that restricts the extent of the heated zone around the line heat source point, as shown in Fig. 5, which can affect significantly the overall thermally induced volume change.

Figure 7 shows the comparison between the consolidation behavior of the reference test that conducted at room temperature and the thermo-mechanics test where the soil temperature and the vertical stress were increased simultaneously. The final settlement of the thermo-mechanics test is higher than the reference test. This difference in the final settlement can be attributed to the thermal consolidation effect as shown in Fig. 6. The lower initial settlement of the thermo-mechanics test in the early stage can be attributed to the thermal expansion of soil water that require some time to drain out due to the low permeability. However, the results also show that the consolidation rate of the thermo-mechanics test is higher than the reference test. This behavior can be interpreted in light of the increase of soil permeability as the temperature increase.

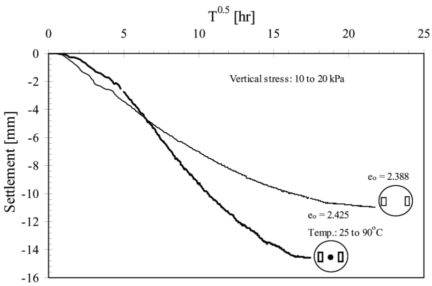

Figure 7. Consolidation rate at different temperatures.

Based on the previous discussion, it can be concluded that the thermo-mechanics path with PVD has significant affect on the consolidation rate. Therefore, it can be considered as promising approach since it enhances the performance of pre-loading with PVD by reducing significantly the consolidation time.

5 CONCLUSIONS

Based on the test results of thermal consolidation path and thermo-mechanics path that conducted using large oedometer apparatus, the following points can be concluded:

- The thermal consolidation path with PVD is non-successful approach since the low thermal conductivity of soil restricts the extent of the heated zone around heat point which can affects significantly the overall thermally induced volume change.
- The thermo-mechanics path with PVD shows promising results. It enhances the performance of pre-loading with PVD by reducing significantly the consolidation time.

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