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NOVEL THERMO-PVD CONSOLIDATION TECHNIQUE FOR SOFT SOILS

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ABSTRACT: Previous research efforts on investigating the thermo-hydro-mechanical behaviour of fine grained soils as well as recent extensive experiments conducted on soft Bangkok clay have demonstrated that saturated fine-grained soils subjected to temperature less than boiling point of water (100^{o}C) undergo volumetric and shear strength changes depending on the stress history. These features encouraged employing the thermal load only, up to 90^{o}C, or in combination with mechanical loading as ground improvement technique. This paper addressed the applicability of this technique through a series of large oedometer tests conducted on soft Bangkok clay. Heating was achieved using flexible wire heater attached to the PVD point or using separate line heat source. The clay has been subjected to either thermal load or thermo-mechanical load. The test results show that a combination of the thermal and mechanical load gives promising results and is a viable technique since it accelerates the rate of consolidation and increases the amount of total settlement. This behavior can be attributed to the increase in the soil hydraulic conductivity as the soil temperature increases. Therefore, raising the soil temperature during the preloading period can enhance the performance of the PVD, particularly, by reducing the drainage retardation effects due to the smear zone around PVD.

Keywords: Thermal consolidation, temperature effects, Bangkok clay, prefabricated vertical drain (PVD), ground improvement

INTRODUCTION

Construction of road embankments on top of soft normally consolidated clay deposits requires pre-consolidation and strengthening of the weak compressible soils. Prefabricated Vertical Drains (PVD) are time tested, very effective and economical ground modification technique in such deposits. 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 only 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 designed to understand 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 background pertaining to the thermo-mechanical behaviour of soft Bangkok clay is presented in the following section based on the extensive experimental studies that conducted by Abuel-Naga (2006) and Abuel-Naga et al. (2005, 2006, 2007). Later on, testing equipment, test specimen and experimental program are described in detail. Subsequently, the test results are presented. Then, the analytical prediction for consolidation behavior of full-scale embankment test on soft Bangkok clay using thermo-PVD was conducted and discussed. Finally the conclusions are drawn.

BACKGROUND

During the last three decades, increased interest of radioactive disposal in deep clay formations required 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

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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 (2006) to investigate the thermo-hydro-mechanical behaviour of soft Bangkok clay. The test results from oedometer tests where the specimen temperature was raised up to 90°C under fully drained constant stress condition have shown that the thermally induced volume change is stress history dependent as illustrated in Fig. 1(Abuel-Naga et al. 2005, 2006). 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 as shown in Fig. 2. The effect of temperature on hydraulic permeability of soft Bangkok clay was also investigated by Bergado et al. (2004). Flexible wall permeameter tests were conducted at different temperatures up to 90°C. The results have indicated that as the soil temperature increased the hydraulic conductivity also increased as shown in Fig. 3. This behaviour was attributed to the thermal evolution of the pore soil liquid viscosity.

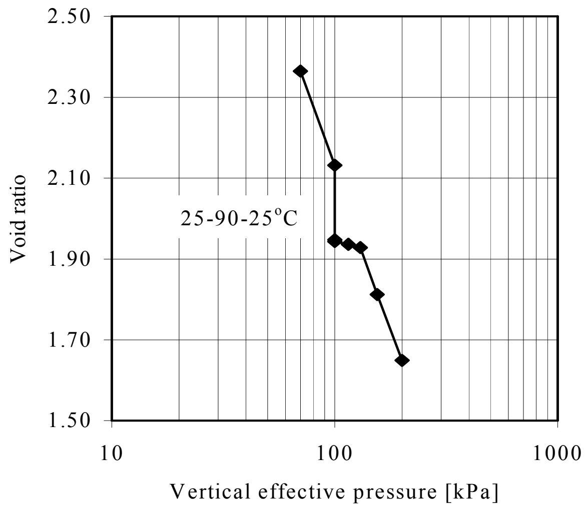


Fig. 2 Temperature induced overconsolidation state of normally consolidated soft Bangkok clay after drained heating/cooling cycle

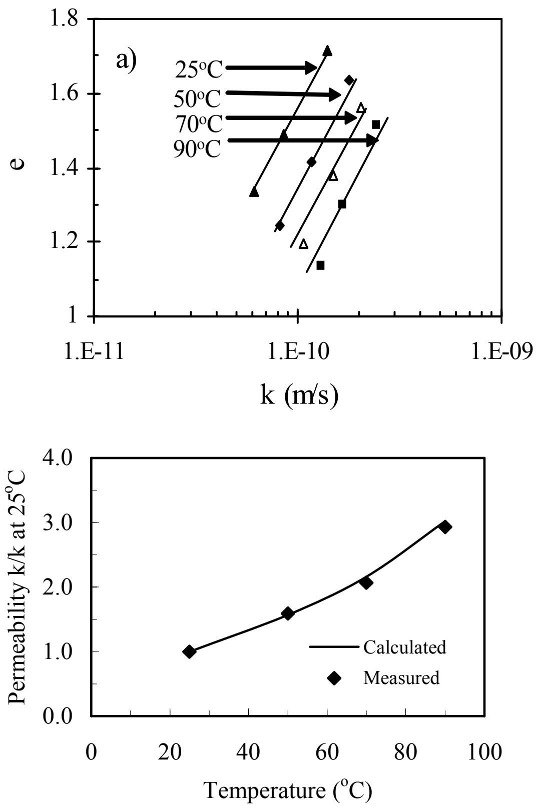


Fig. 3 (a) Effect of temperature on hydraulic conductivity of soft Bangkok clay, (b) effect of temperature on k at constant void ratio

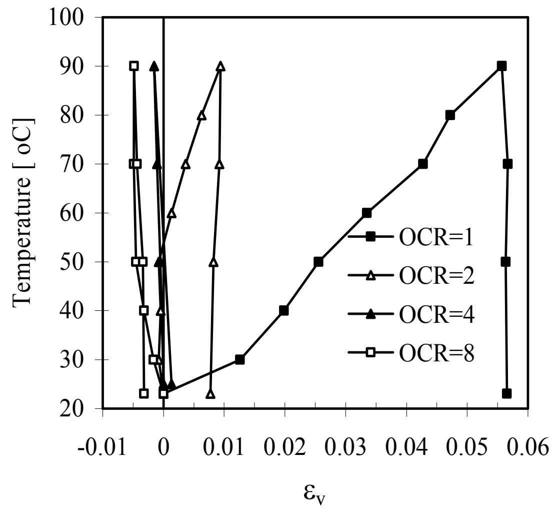


Fig. 1 Soft Bangkok clay temperature volumetric strain under drained heating/cooling cycle at different OCR values (preconsolidation pressure = 200 kPa)

Abuel-Naga et al. (2006, 2007) investigated 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.

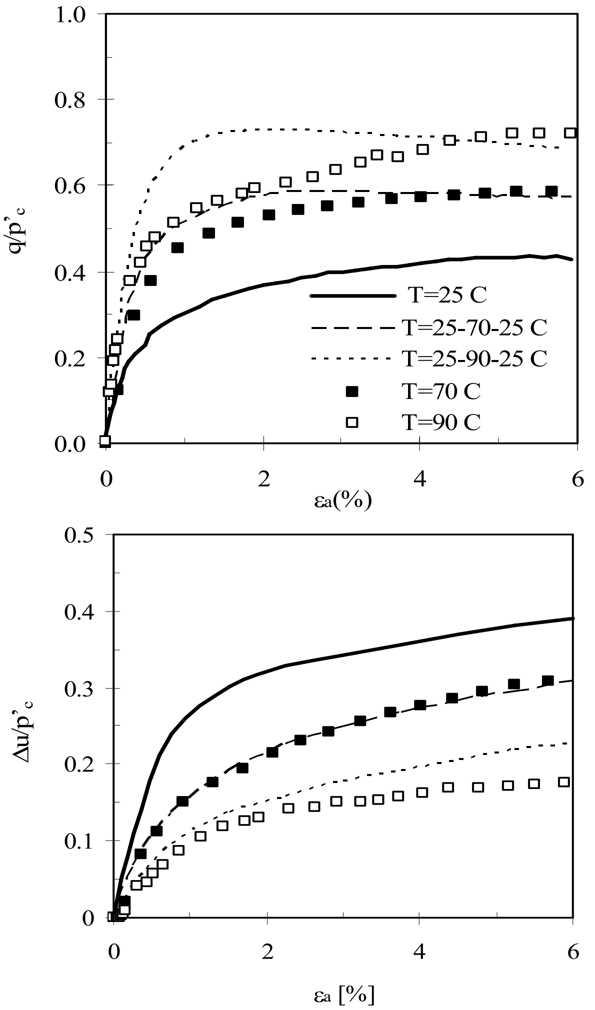


Fig. 4 Undrained triaxial compression test results of normally consolidated soil tested at different temperatures or after subjecting to different heating/cooling cycles

Temperature history implies 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 as shown in Fig. 4.

These findings encouraged the authors to explore the potential of employing the PVD system with thermal load only or in combination with mechanical load as ground improvement technique.

TEST SPECIMEN

The soft Bangkok clay samples obtained from 3.0 to 4.0 m depth have been used in this study. Table 1 shows the physical properties of soft Bangkok clay. The mineralogical composition as reported by Ohtsubo et al. (2000) using XRD shows that the soft Bangkok clay consists of Smectites (Montmorillonites and Illites) ranging from 54 to 71% with Kaolinites (28 to 36%) and micas.

TEST EQUIPMENTS

Large oedometer apparatus was utilized in this study to investigate the effect of soil temperature on the performance of PVD. Dead load was used to apply the required vertical stress as shown in Fig. 5. For reconstituted specimens, large oedometer cell that can accommodate soil specimen up to a height of 200 mm and diameter of 300 mm was used. However, large oedometer cell with inner diameter of 200 mm was utilized for testing the undisturbed specimens. Dial gauge was provided to monitor settlement during the consolidation process. The soil temperature was raised using line heat source either attached to PVD point

Table 1 Physical properties of soft Bangkok Clay

Liquid limit (%)	103
Plasticity index	60
Water content (%)	90-95
Liquidity index	0.62
Grain Size Distribution	
Clay (%)	69
Silt (%)	28
Sand (%)	3
Total unit weight (kN/m^3)	14.3
Dry unit weight (kN/m^3)	7.73
Specific gravity	2.68
Specific surface area (m^2/g)	237

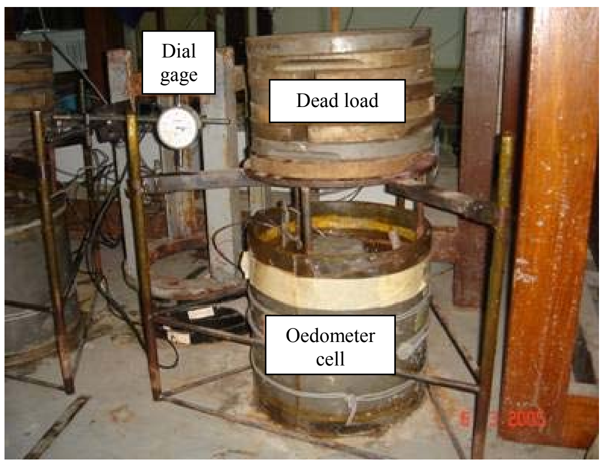


Fig. 5 Large oedometer apparatus

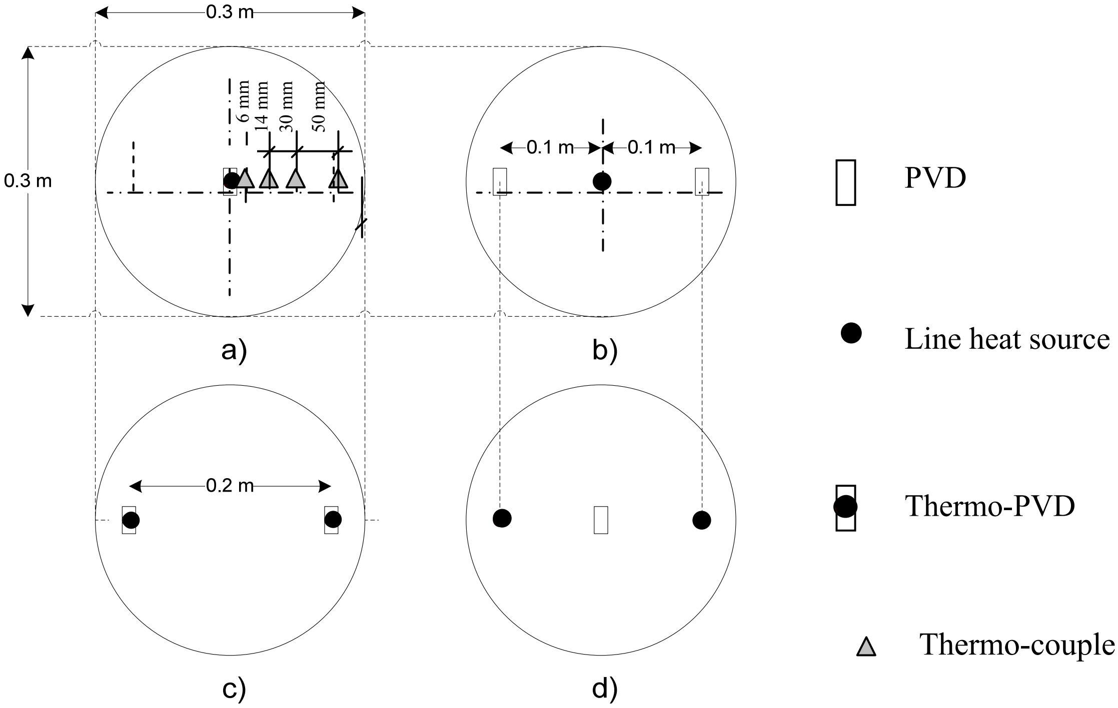


Fig. 6 Different arrangements of Thermo-PVD, PVD, and heater spacing of line heat source in large oedometer cell

(Thermo-PVD) or installed independently between the PVD points. Figure 6 shows 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 placed in the grooves as shown in Fig. 7a. The separate line heat source was created by wrapping flexible wire heater around a metal plate with 20 mm wide and 200 mm long as shown in Fig. 7b. For both types of line heat source, a thermocouple (K-type) was placed at the mid-height of line heat source with direct contact with the surrounding soil.

This thermocouple was used for both temperature measurements and the feedback signal for the thermo-controller unit.

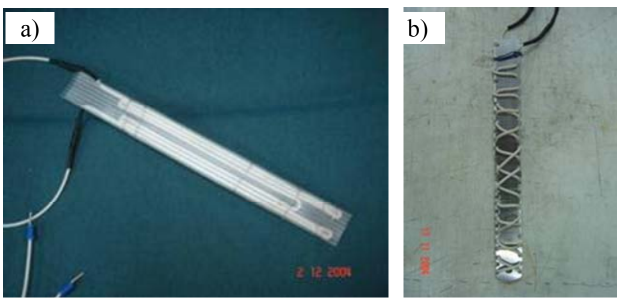
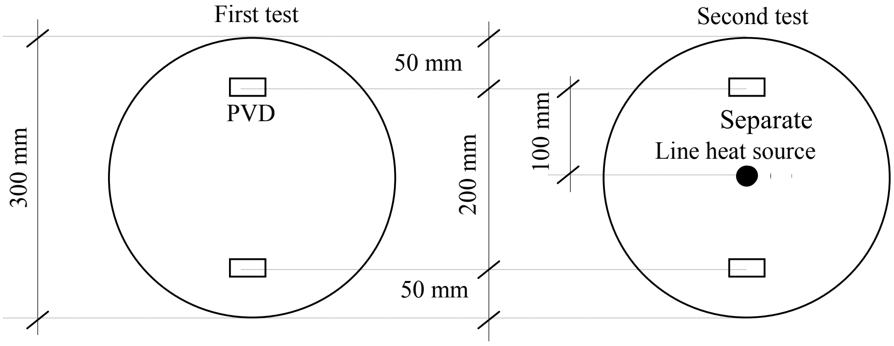


Fig. 7 a) Thermo-PVD configuration; b) Line heat source configuration

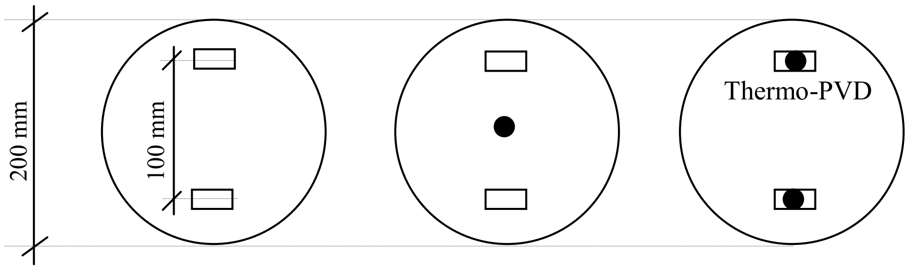
EXPERIMENTAL PROGRAM

Reconstituted and undisturbed soft Bangkok clay specimens were tested by Chaiprakaikeow (2005). The reconstituted sample was prepared by applying a consolidation pressure of 10 kPa to the remolded sample. The remolded sample was prepared by adding a sufficient amount of water until its water content was about 1.2 times greater than its liquid limit. The sample was then thoroughly mixed in a mechanical mixer and transferred in layers into the testing container. All reconstituted samples were loaded until 90 % consolidation was achieved. The experimental programs of the large oedometer test apparatus was directed to investigate the heat transfer behavior in saturated soils around line heat source. Moreover, thermal consolidation as well as thermo-mechanical consolidation behavior of soft Bangkok clay using line heat source and PVD was also investigated.

The heat transfer study involved measurement of soil temperature change at different distances from thermo-PVD point of 90^{o}C constant temperature. Thermo-couples were inserted at the mid-height of the reconstituted soil specimen with different r/r_e ratios (1.0,



a) Reconstituted specimen



b) Undisturbed specimen

Fig. 8 Thermo-mechanical consolidation test configurations

3.34, 8.34, 16.67) as shown in Fig.6a, where r and re 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.

The thermal consolidation study of reconstituted specimens involved raising the temperature of thermo-PVD or separate line heat source point up to 90°C at constant effective stress condition and measuring the thermally induced volume change with time. Four specimens with different configurations of thermo-PVD, PVD, and separate line heat source were tested under thermal consolidation condition as shown in Fig. 6.

On the other hand, the thermo-mechanical consolidation study of reconstituted specimen involved raising simultaneously both 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 with time. Two tests were conducted in this study as shown in Fig. 8a. The first test is considered as reference consolidation test where the thermal effect is not included. The specimen of the second test was provided by line heat source point in its center to apply the thermal load.

The thermo-mechanical consolidation path was also investigated for undisturbed specimens (preconsolidation pressure = 75 kPa) as shown in Fig. 8b. Two different configurations of line heat source point were tested under the thermo-mechanical path where the vertical effective stress was increased from 0.0 to 30 kPa (OCR=2.5) and the temperature of the line heat source was raised from 25 to 90°C, simultaneously. Reference test was also conducted where only the vertical effective stress was increased from 0.0 to 30 kPa while the soil temperature was not changed. The settlement induced by mechanical (reference test) and thermo-mechanical path was measured with time. The vertical effective stress value (30 kPa) was the maximum stress that can be applied due to the limitation of the utilized dead load application technique.

TEST RESULTS AND DISCUSSIONS

Heat Transfer around Line Heat Source

The temperature-distance relationship at steady state condition is plotted in T/T_o-r/r_e plane as shown in Fig. 9, where T and T_o are the measured and room temperature (25°C), respectively. The steady state condition was achieved after 15 hr from the beginning of the test as shown in Fig. 10. The test results indicate that the temperature change around the thermo-PVD decreases as the radial distance increases and becomes constant in the zone defined as $r/r_e \geq 8.0$, 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.

Thermal Consolidation with PVD

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 are plotted in settlement versus square root time as shown in Fig. 11. For the samples S1 and S2 that contain one PVD point, the final thermally induced settlement was approximately equal to 3.9 mm. However, the sample S2 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 dissipation behavior. For sample S2 with thermo-PVD, the drainage point is located at the center of the maximum temperature zone. Thus, faster dissipation of the thermally induced pore water pressure is expected.

Similar behavior was observed for the specimens that contained two PVD points as demonstrated by the result of samples S3 and S4, respectively. The final thermally induced settlement for the samples containing two PVD points was approximately equal to 5.0 mm. Based on these results, it can be concluded that for normally consolidated specimen, the volume changes generated by thermal consolidation path with PVD at constant effective vertical stress condition are insignificant. The low value of thermal consolidation with PVD can be attributed to the low thermal conductivity of clay specimens that restricted the extent of the heated zone around the line heat source point as demonstrated in Fig. 15, which affected significantly the overall thermally induced volume change.

Thermo-Mechanical Consolidation with PVD

The thermo-mechanical consolidation refers to the simultaneous increases of soil temperature and effective stress. For reconstituted specimen, Fig. 12 shows the comparison between the consolidation behavior of the reference test specimen subjected to mechanical consolidation (the effective stress was increased from 10 to 20 kPa) at room temperature (25^{o}C) and the thermo-mechanical test specimen where the soil temperature and the vertical stress were increased simultaneously (the effective stress was increased from 10 to 20 kPa and the heat source temperature was raised from 25 to 90^{o}C).

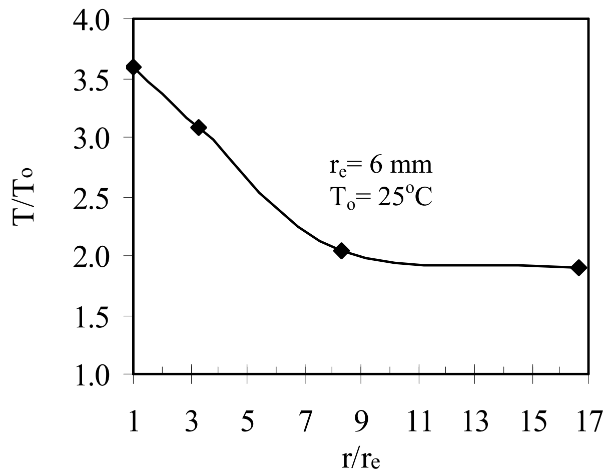


Fig. 9 Temperature-distance relation at steady state condition around thermo-PVD point

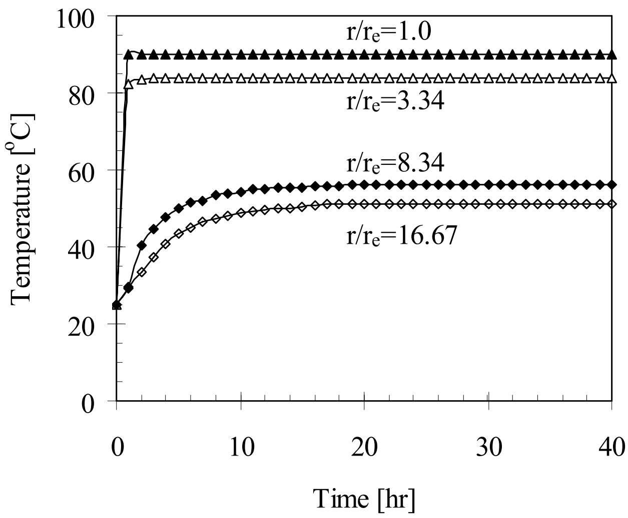


Fig. 10 Temperature change with time at different distances from Thermo-PVD point with constant temperature of 90^{o}C and equivalent radius, r_e= 6 mm

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 as shown in Fig. 11. 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 15 days while the corresponding value of the settlement can be obtained after only 5 days using thermo-mechanical path. This behavior can be attributed to the increased soil hydraulic conductivity as the temperature increased as shown in Fig. 3. Consequently, the negative effect of the smear zone on the drainage can be reduced by the thermal effect. Thus, the thermo-mechanical path with PVD has increased significantly the consolidation rate. Therefore, it can be considered as promising approach since it enhanced the performance of preloading with

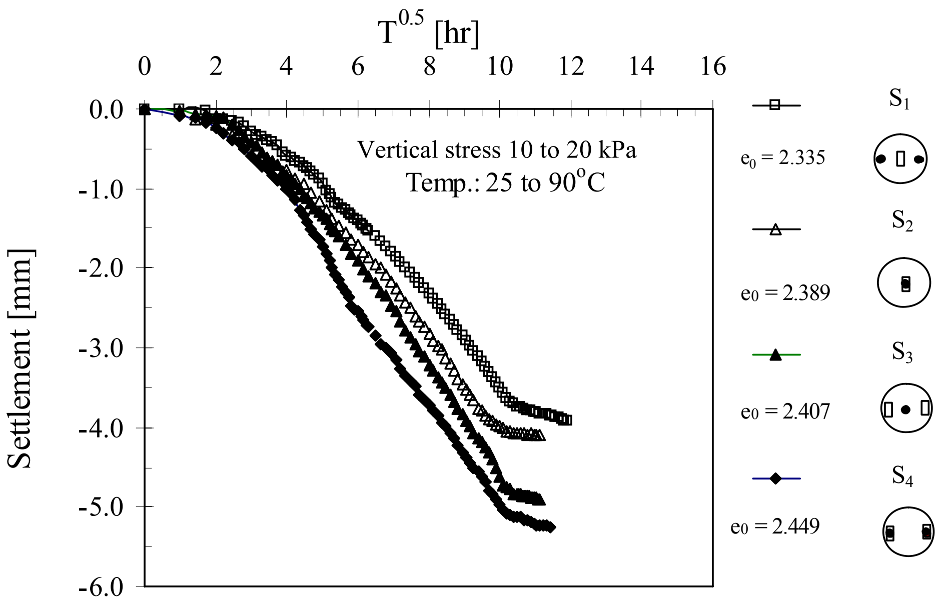


Fig. 11 Thermal consolidation test results

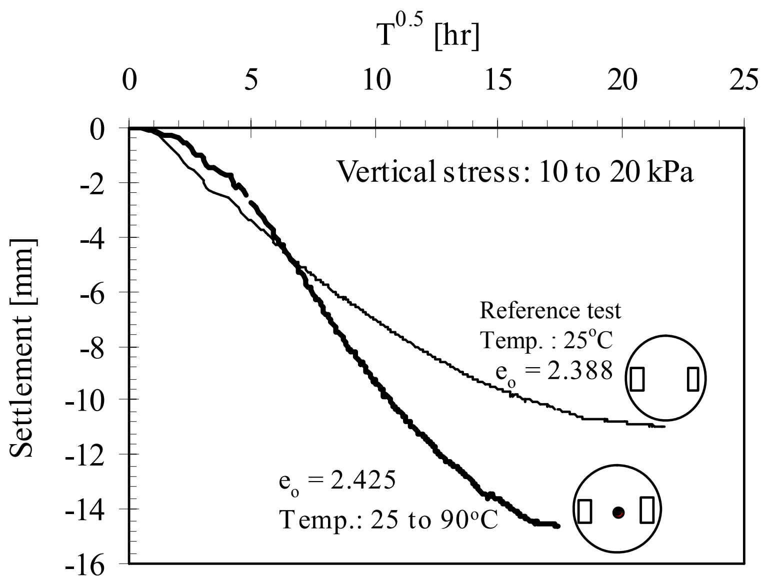


Fig. 12 Thermo-mechanical consolidation test results of reconstituted specimen

PVD by reducing the consolidation time to approximately one third of the consolidation time at room temperature.

The results in Fig. 13 indicate that similar effect of temperature on consolidation rate can be also observed for undisturbed specimens. Moreover, the results also show that using thermo-PVD (PVD and line heat source at the same location) is preferable than the separate line heat source since the thermo-PVD induced higher consolidation rate. The advantage of the thermo-PVD can be attributed to the coincidence of the drainage point and the smear zone at the center of the maximum temperature zone. Consequently, significant reduction of the smear effect can be achieved in this case.

ANALYTICAL PREDICTION FOR CONSOLIDATION BEHAVIOR OF FULL-SCALE EMBANKMENT TEST ON SOFT BANGKOK CLAY USING THERMO-PVD

A 4.0-m-high test embankment preloading was constructed by Bergado et al. (1992) on improved ground with prefabricated vertical drains to study the

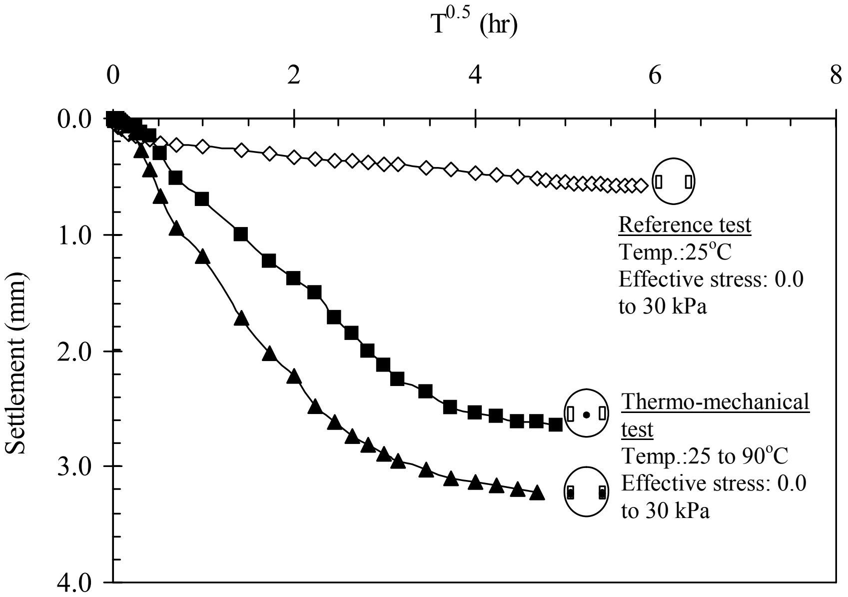


Fig. 13 Thermo-mechanical consolidation test results of reconstituted specimen.

effectiveness of PVDs on soft Bangkok clay. The drains were installed in triangular pattern at 1.5 m center-to-center spacing by means of a special mandrel to a depth of 8.0 m. A rectangular-shaped mandrel was used, which had inner dimensions of 28.0 mm by 133.0 mm and outer dimensions of 45.0 mm by 150.0 mm, just large enough to contain the 3.0 mm by 95.0 mm Mebra prefabricated vertical drains made of geotextiles. The embankment plan and section views, including the layout of prefabricated vertical drains, are shown in Fig. 14a, b. Figure 15 shows the observed surface settlement during the consolidation process under the embankment load.

In the following, the prediction approached used by Bergado et al. (1992) to simulate the PVD consolidation results will be presented then the effect of temperature on the soil parameter will be utilized to predict the consolidation behaviour of the proposed thermal technique using thermo-PVD.

Consolidation Behaviour using PVD

The initial settlement, ρ_i, can be estimated as follows:

$$\rho_i = qBI\left(\frac{1-\nu^2}{E_u}\right) \tag{1}$$

where q = the loading pressure; B = the width of the embankment; I = an influence factor considering a rough rigid base; and E_u= the undrained modulus

The general form for the average degree of consolidation of soil cylinder containing a central drain can be derived using Barron (1948) approach that was modified by Hansbo (1979) and expressed in the following form:

$$t = \left[\frac{D_e^2}{8c_h}\right]\left[F(n) + F_s + F_r\right]\ln\left(\frac{1}{1-U_h}\right) \tag{2}$$

where D_e = the diameter of the equivalent soil cylinder; c_h = the horizontal coefficient of consolidation; t= the time after an instantaneous increase of the total vertical stress; F(n) = the factor that expresses the additive effect due to the spacing of drains. F_s and F_r are the smear effect and well resistance, respectively. Hansbo (1979) gave the following expressions for the spacing, well resistance, and smear factors, respectively:

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

$$F_r = \Pi z(L-z)\left(\frac{k_h}{q_w}\right) \tag{4}$$

$$F_s = \left(\frac{k_h}{k_s} - 1\right)\ln\left(\frac{d_s}{d_w}\right) \tag{5}$$

$$F = F(n) + F_r + F_s \tag{6}$$

where d_s = the diameter of the smeared zone; L = the length of the drain when opened at one end only; z = the vertical distance from opened end of drain; k_s = the permeability of the disturbed zone in the horizontal direction; k_h = the horizontal hydraulic permeability; and

q_w = the discharge capacity of the drain. FEM analysis (Rixner et al. 1986) showed that the equivalent diameter of the drain (d_w) can be obtained as follows:

$$d_w = (a+b)/2 \tag{7}$$

where a and b = the thickness and width of the band-shaped drain, respectively.

The back-analysis of the consolidation results of the embankment conducted by Bergado et al. (1992) recommended the following values for the soil parameters and the smear zone configuration around PVD point:

$$c_h = 4.9\ m^2/year$$
$$k_h/k_s = 10$$
$$d_s/d_w = 2.5$$
$$E_u = 3000\ kPa$$

The prediction of the consolidation results using the above mentioned values fit well with the observed results as shown in Fig. 15.

Consolidation Behaviour using Thermo-PVD

In case of utilizing thermo-PVD, with temperature 90°C, instead of the conventional PVD system the

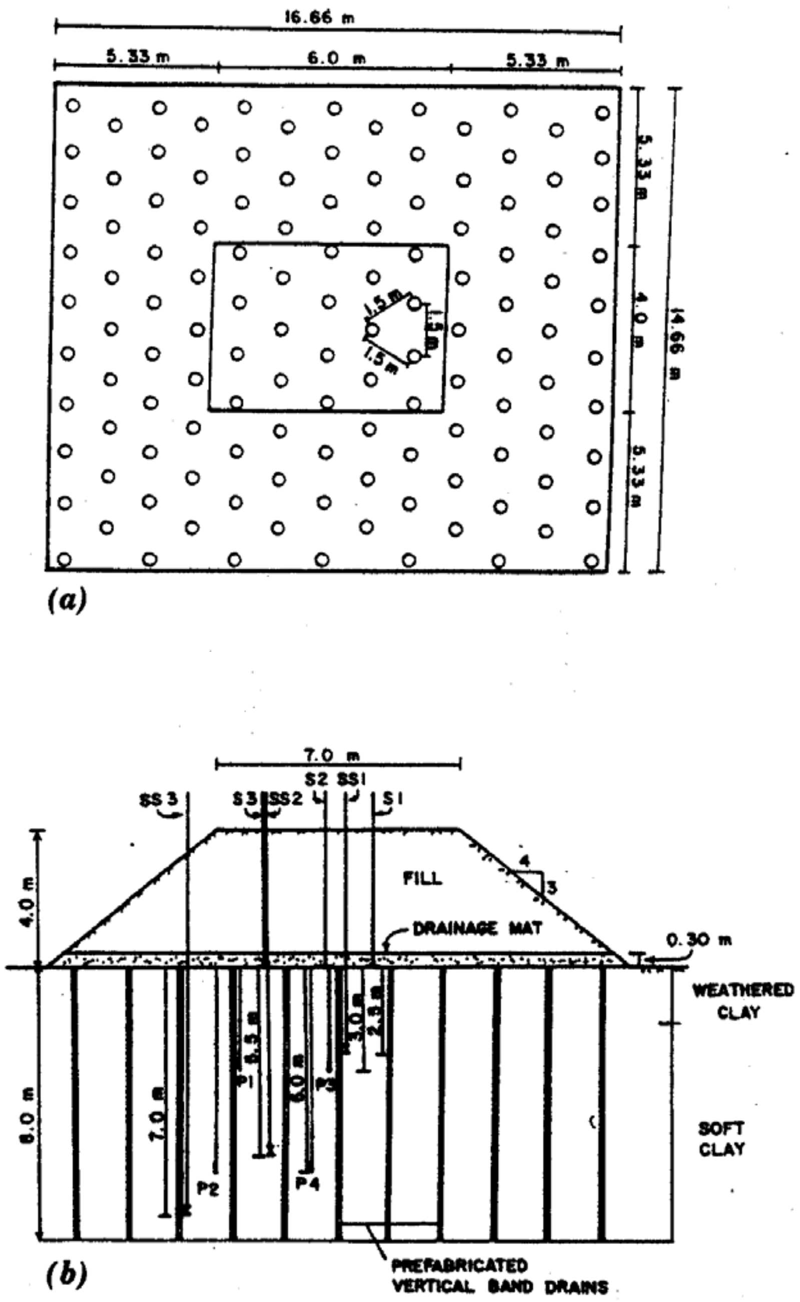


Fig. 14 Embankment plan, section view and layout of field instrumentation at PVD site (Bergado et al. 1992)

horizontal hydraulic conductivity in the smear zone (k_s) will increases due to the increase of the water viscosity of the pore soil water. The test results of heat transfer around linear heat source with constant temperature of 90°C (Fig. 9) indicated that within the smear zone (d_s=2.5 d_w) the temperature varied from 80 to 90°C. Therefore, the increase of the horizontal hydraulic conductivity of the smear zone due to the imposed thermal load can be estimated as follows (Fig. 3b)

$$(k_s)^{\text{Thermo-PVD}} = 2.75\,(k_s)$$

Moreover, the test results of heat transfer around linear heat source with constant temperature of 90°C show that soil temperature beyond the smear zone will be also raised. An average temperature value of 50°C in this zone can be expected. Consequently, the horizontal hydraulic conductivity of this zone will increase due to the temperature increase as follows (Fig. 3b)

$$(k_h)^{\text{Thermo-PVD}} = 1.5\,(k_h)$$

Consequently, in the case of Thermo-PVD system:

$$(k_h/k_s)^{\text{Thermo-PVD}} = (10/2.75)*1.5=5.45$$

$$c_h^{\text{Thermo-PVD}} = 1.5\,c_h$$

Figure 15 illustrates the predicted consolidation results using the thermo-PVD system taking into consideration the temperature effects on the horizontal hydraulic conductivity as discussed above. The results show significant improvement in the consolidation rate using thermo-PVD system. Based on Asaoka (1978), 90% of consolidation settlement (324 mm) occurred at 430 days for the conventional PVD system. The predicted consolidation results of thermo-PVD systems indicated that such settlement can be occurred at 182 days. Therefore, the thermo-PVD system significantly accelerated the ground improvement process.

Full-scale test results for embankment on soft clay using the proposed thermo-PVD system are required to confirm the validity of the proposed thermal technique. This type of embankment is being built in AIT in order evaluate the potential of the proposed technique as well as to simulate numerically the observed behavior.

CONCLUSIONS

Based on the experimental results of the large oedometer tests, the following conclusions can be drawn:

- The thermal consolidation path with PVD of normally consolidated specimen at constant vertical effective stress condition resulted in insignificant contraction volume change. The low thermal conductivity of soil restricted the extent of the heated zone around heat point which significantly affected the overall thermally induced volume change.
- The thermo-mechanical path with PVD which involved increasing simultaneously both the soil temperature and the vertical effective stress shows promising results. It enhances the performance of preloading with PVD by reducing significantly the consolidation time. This behavior can be attributed to the increase of the soil permeability at elevated temperatures which can neutralize the detrimental effects of the smear zone.
- The results of the thermo-PVD, where the drainage combined with the heat line source, performed better

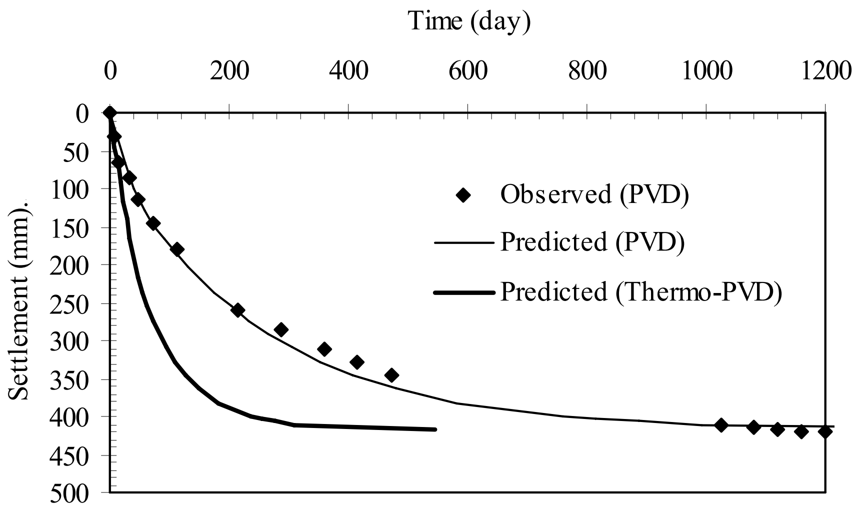


Fig. 15 Comparison between predicted surface settlement using PVD and thermo-PVD system and the observed vertical settlement for PVD system

than the case where the PVD and heat line source were separated.

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