Settlement characteristics of full scale test embankment on soft Bangkok clay improved with Thermo-PVD and stiffened deep cement mixing piles

Comportement des tassements d'un remblai d'essai grandeur nature construit sur de l'argile fine de Bangkok avec des PVD thermiques et des colonnes de sols en DCM renforcé (SDCM)

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ABSTRACT
The full scale test embankments were constructed on improved soft Bangkok clay in Thailand. The ground improvement methods consist of thermal treatment with drainage (Thermo-PVD) and reinforced deep cement mixing (SDCM). This study aimed to compare the reduction of settlements among those aforementioned full scale test embankments. The observed settlements data in field situation also discussed by means of rate and magnitude of the settlements. The Thermo-PVD treated embankment foundation indicated both higher rate and magnitude of settlements. Moreover, the SDCM reduced the settlement magnitude by 40% compared to the DCM improvement. Finally, these soft ground improvement techniques are recommended as viable methods for future geotechnical construction projects.

RÉSUMÉ
Le remblai d'essai grandeur nature fût construit en Thaïlande sur de l'argile fine améliorée. Les méthodes d'amélioration du sol consistent en un traitement thermique avec drainage (PVD thermiques) et d'inclusions par "mixing" renforcé (SDCM). Cette étude visait à comparer la réduction des tassements entre les remblais d'essai grandeur nature ci-dessus mentionnés. Les données sur les tassements observés sur le terrain ont également été discutées en termes de taux et de magnitude de tassements. Les fondations des remblais en PVD thermiques indiquaient à la fois un taux et une magnitude plus élevés de tassement. En outre, le SDCM a réduit la magnitude de tassement de 40% par rapport à l'amélioration DMV. En conclusion, ces techniques d'amélioration des sols sont recommandées comme méthodes viables pour de futurs projets de construction géotechniques.

Keywords : Test Embankment, Prefabricated Vertical Drain, Deep Mixing Method, Soft Clay
Mots clef : remblais d'essai, Drains verticaux préfabriqués (PVD), inclusions par mixing, argile molle

1 INTRODUCTION

Infrastructure construction on soft clay leads to long-term settlement problems. To achieve the desired degree of consolidation within a reasonable period, prefabricated vertical drains (PVDs) are normally used (e.g. Bergado et al., 2002). The function of a PVD is to facilitate horizontal flow of water from the consolidating ground, transport it in the vertical direction and discharge it into the drainage layers with as little hydraulic resistance as possible. The installation of prefabricated vertical drains using a mandrel causes disturbance of the clay surrounding the drain, resulting in a smear zone of much lower horizontal permeability than the undisturbed clay. The presence of a smear zone significantly reduces the rate of horizontal consolidation resulting in retardation of the overall consolidation rate (Hansbo, 1981; Bergado et al., 1991; Hird & Moseley, 2000). Abuel-Naga et al. (2006a) investigated at laboratory scale the validity and efficiency of an innovative thermal technique called Thermo-PVD for enhancing the performance of prefabricated vertical drains in soft Bangkok clay. The test results showed that the combination of PVD with the thermal and mechanical load accelerated the rate of consolidation and increased the amount of total settlement. This behavior is attributed to the increase in hydraulic conductivity of the soil around the Thermo-PVD as the soil temperature increased. The promising findings of Abuel-Naga et al. (2006a) leads to the present study of Thermo-PVD with full scale test embankment load.

Deep cement mixing (DCM) pile can effectively reduce settlements of earth embankments on soft ground (Bergado et al., 1999; Lai et al., 2006). However, DCM piles have low strength and stiffness and could lead to low bearing capacity and large settlements with associated quality control problems. Consequently, DCM piles are not suitable for medium to high design loads (Dong et al., 2004). Hence, a new composite structure of DCM with a concrete core at the center of the DCM has been introduced and is called stiffened deep cement mixing (SDCM) pile. The concrete core, which is basically a precast concrete pile, takes most of the load and gradually transmits it to the surrounding soil-cement through the interface between the concrete pile and the DCM. The SDCM pile is more suitable than DCM pile because SDCM pile has higher strength and stiffness and can sustain bending moment caused by horizontal forces. Previously, the behavior of DCM pile under embankment loading on soft Bangkok clay had been studied (e.g. Lorenzo & Bergado, 2006). However, the SDCM pile has not yet been studied. To further investigate the behavior of SDCM pile under embankment loading on soft Bangkok clay, full scale tests of SDCM pile have been conducted in this study.

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2 TEST EMBANKMENT ON SOFT GROUND IMPROVED WITH THERMO-PVD

The extensive experimental work that were carried out by several researchers (Cekerevac & Laloui, 2004) on some European deep clays and others artificial remolded clays have conclusively demonstrated that increasing the temperature of saturated clays to less than the boiling point of water (100^{o}C), affects positively its engineering properties (permeability, compressibility, and shear strength). Abuel-Naga et al. (2006b) performed flexible wall permeameter tests at different temperatures up to 90^{o}C to investigate the temperature effect on hydraulic conductivity of soft Bangkok clay. The results have indicated that as the soil temperature increased the hydraulic conductivity also increased. This behavior was attributed to the thermal evolution of the pore liquid viscosity of the soil.

The site of the embankment tests is located inside the campus of the Asian Institute of Technology (AIT), within the Central Plain of Thailand that contains the deltaic-marine deposit of soft clay layer widely known as "soft Bangkok clay". The typical stratigraphy at the location of AIT consists of the top weathered crust of dark brown clay from the ground surface to about 2.0 m depth. This layer is underlain by soft, highly compressible, gray clay down to about 8.0 to 9.0 m depth. Below the soft clay layer lies about 6.0 m thick of stiff clay. The ground water table fluctuates with the season with an average value of 2.0 m below the ground level. The geotechnical profile of the site is shown in Figure 1.

Two identical 6.0 m high full-scale embankments were constructed at AIT site where the distance between them is 60.0 m. Conventional PVD system was installed underneath the first embankment whereas a modified (Thermo-PVD) was utilized for the second one. Figure 2 shows the general layout of one of the constructed embankment. The dimensions of the embankments are 11 m x 11 m at the bottom and 3 m x 3 m at the top. The fill material consisted of compacted silty sand.

Nine PVD/Thermo-PVD were installed to 8.0 m depth beneath the embankment on a square grid of 1.0 m spacing. A commercial PVD with 100 mm × 4.3 mm cross-section was utilized in this study. The Thermo-PVD unit consists of a U-tube made of cross-linked polyethylene plastic (PEX) attached to a conventional PVD unit as shown in Figure 3. Preheated water at about 70 to 90^{o}C is circulated through the attached U-tube to raise the temperature of the clay adjacent to the Thermo-PVD underneath the embankment. A solar panel system was used to heat the circulated water from ambient temperature (25^{o}C) to 72^{o}C. Then, an electrical heater was utilized to raise its temperature from 72^{o}C to 90^{o}C. A special water pump able to work at elevated temperatures was used to circulate the hot water through the Thermo-PVD.

The monitoring system of Thermo-PVD embankment consisted of settlement plates installed 0.3 m away from the central Thermo-PVD point at three different depths (0.0, 3.0, 6.0 m) as shown in Figure 2. On the other side of the central Thermo-PVD two pairs of thermo-couples were installed at 3.0 and 6.0 m depth. Furthermore, two pore water pressure (pwp) transducers were installed 0.3 m away from the central Thermo-PVD point at two different depths (3.0, 6.0 m). The monitoring system of the PVD embankment is similar to the Thermo-PVD embankment. The testing program of PVD and Thermo-PVD embankment include embankment building stage then mechanical consolidation stage for PVD embankment and thermo-mechanical consolidation stage for Thermo-PVD embankment. During these two stages, temperatures, pore pressures, and settlement readings were collected at different time intervals. The thermo-mechanical consolidation stage involves circulation of hot water (70 to 90^{o}C) through the Thermo-PVD system. The heating stage lasted for 110 days until the primary consolidation was completed. Then, the whole system was left to cool down for about 90 days. The stress condition indicated that the soft clay layer located between 2.0 to 7.0 m depth is under the normally consolidated condition. The settlement results of two embankments are plotted in Figure 4a,b. In general, the Thermo-PVD embankment yields more and faster rate of settlement.

The settlement data of the layer from 0.0 to 6.0 m depth were analyzed. The change in the thickness of this layer (ΔH) was calculated using the measurements of the settlement plate at surface, So, and at 6.0 m depth, S6, ($\Delta H = S_o - S_6$). The excess pore water pressure measurements at 3.0 m depth were used to determine the end of the primary consolidation stage. Thermo-PVD embankment shows higher excess pore water pressure than PVD embankment due to thermally induced pore water pressure and volume change. The thermally induced pore water pressure is generated because the thermal expansion coefficient of water is 15 times larger than the soil solids.

The difference in ΔH between two embankments is attributed to the thermal consolidation at Thermo-PVD embankment which shows irreversible behavior upon cooling. The results also show that the consolidation rate of Thermo-

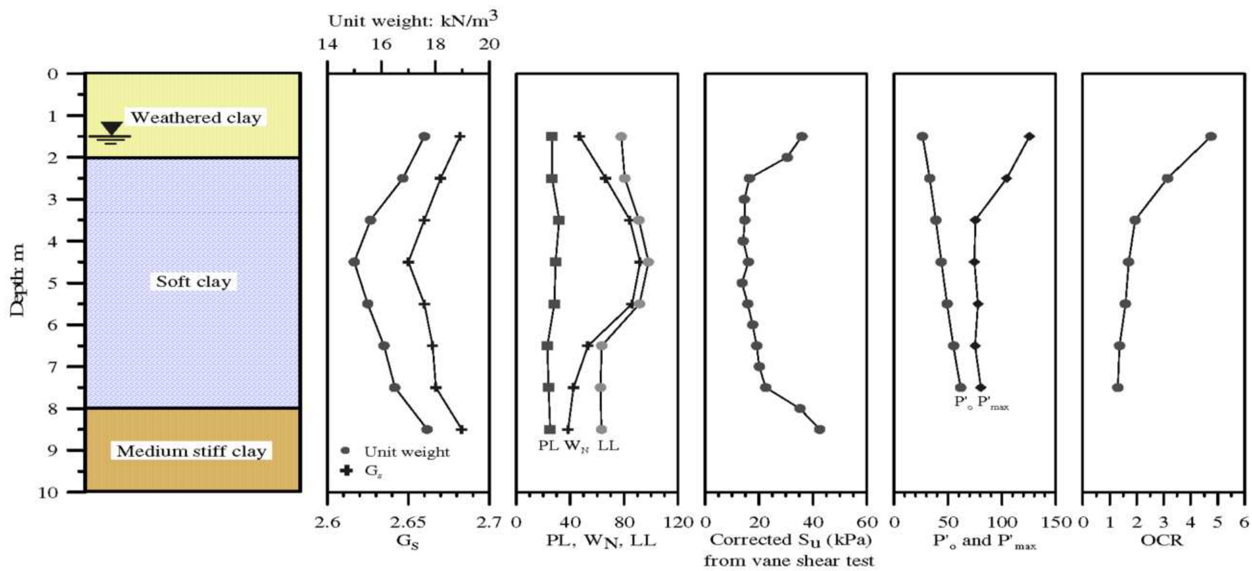

Figure 1. Soil profiles under the test embankment: G_s, specific gravity; *PL*, plastic limit; w_N, natural water content; *LL*, liquid limit; S_u, undrained shear strength; P'_o, overburden effective stress; P'_{max}, the maximum past pressure

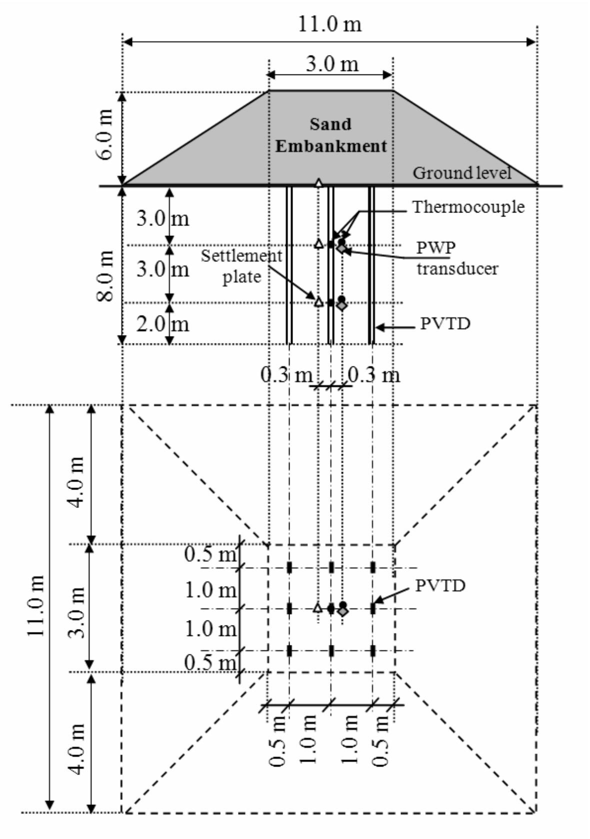

Figure 2. Layout of full-scale thermo-PVD embankment

PVD embankment is higher than PVD embankment. The amount of consolidation generated by PVD embankment at end of its primary consolidation stage (after 80 days) can be achieved after 25 days for Thermo-PVD embankment. This behavior can be explained in light of the increase in hydraulic conductivity at elevated temperature as the result of the thermal evolution of water viscosity (Abuel-Naga et al., 2006b).

Using the measurements of the settlement plate at 3.0 m depth, the change in the thickness of the layer between 0.0 to 6.0 m depth (ΔH) can be broken down into two components representing the change in the thickness of the layer between 0.0 to 3.0 m depth (ΔH_1), and the layer between 3.0 to 6.0 m depth (ΔH_2). The results illustrated that Thermo-PVD and PVD embankment yielded approximately similar ΔH_1 whereas there is a significant difference in ΔH_2 between Thermo-PVD and PVD embankment. This behavior can be attributed to the difference in the soil type between the two layers. The first layer (from 0.0 to 3.0 m depth) includes about 1.0 m of compacted sand, 1.0 m of dry compacted clay, and 1.0 m of soft clay whereas the second layer (from 3.0 to 6.0 m depth) contains only soft clay.

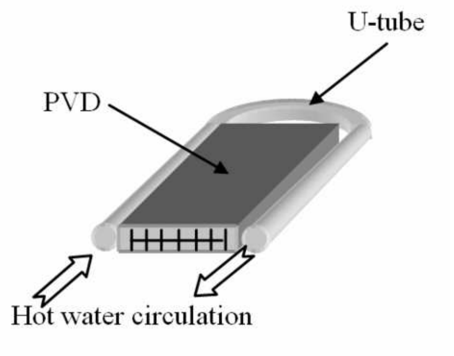

Figure 3. Thermo-PVD configuration

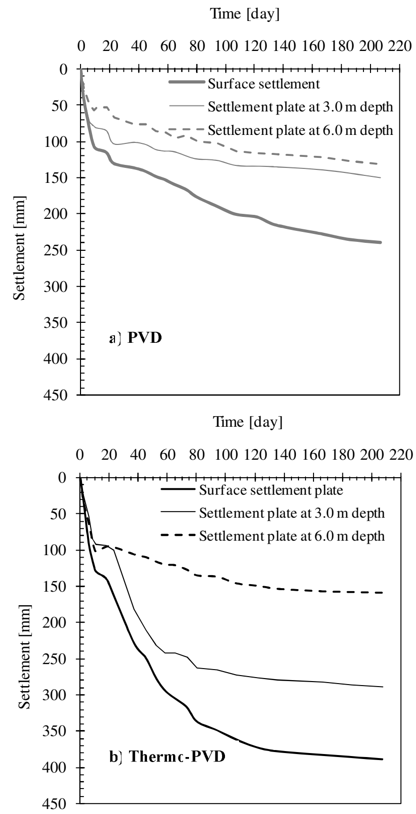

Figure 4a,b. Settlement results of PVD and Thermo-PVD embankments

3 TEST EMBANKMENT ON SOFT GROUND IMPROVED WITH DEEP CEMENT MIXING

A 5 m high test embankment was constructed at the campus of Asian Institute of Technology. The soil profile and their properties are shown in Figure 1. Prior to embankment construction, the foundation subsoil was improved with DCM pile and SDCM pile, which were installed in situ by a jet mixing method employing a jet pressure of 22 MPa. Deep mixing piles were installed at 2.0 m spacing in square pattern as shown in Figures 5a, b. The water-cement ratio (w/c) of the cement slurry and the cement content employed for the construction of deep mixing piles were 1.5 and 150 kg/m^3 of soil, respectively. Each deep mixing pile has a diameter of 0.60 m and length of 7.0 m, penetrating down to the bottom of the soft clay layer as shown in the section view of the embankment (Figure 5b). A pre-stressed concrete core pile was inserted at the center of the soil-cement slurry to form the SDCM pile. The pre-stressed concrete core was square section with 0.22 m in width and 6.0 m in length. The monitoring instruments were installed 30 days after the DCM and SDCM installations. Then, the full scale test embankment was constructed.

Firstly, trench excavation was done by excavating weathered clay layer at depth of 1 m. and the area covered by test embankment was backfilled with compacted silty sand with 1.0 m thickness. Then, a 5 m high embankment with the slopes of 1:1 and 1:1.5 on North-South side and East-West side, respectively, was constructed with base dimensions of 19 m by 21 m and top dimensions of 9 m by 6 m using weathered clay and silty sand as fill materials with compacted unit weights of 17.0 and 16.0 kN/m^3 respectively. The embankment construction was completed within 30 days.

Figure 6 shows the settlements on top of SDCM pile, DCM pile, surrounding clay of SDCM pile, surrounding clay of DCM pile and on the surface of unimproved clay during and after construction up to 570 days of full embankment loading. From

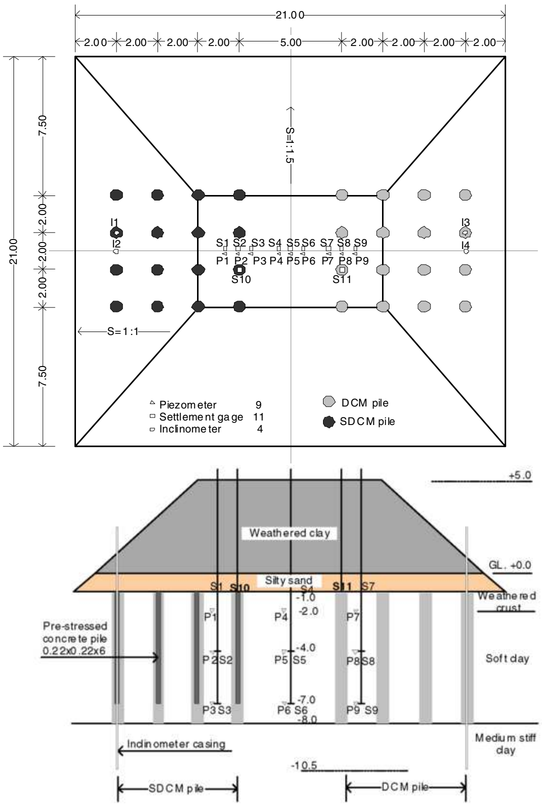

Figure 5 Plan and section views of test embankment supported by DCM and SDCM piles

these actual observed data, the settlements on SDCM pile, DCM pile and on unimproved clay amounted to about 97, 128, 118, 167 and 175 mm, respectively, after embankment construction. The settlements on SDCM pile, DCM pile and unimproved clay amounted to about 161, 265, 250, 296 and 353 mm, respectively, at 570 days after embankment construction. Approximately, 50% of the total settlement occurred during the construction of the test embankment. The settlement on surrounding clay of SDCM pile is less than that on surrounding clay of DCM pile. Thus, the embankment load (weight of embankment) has been transferred to the SDCM pile more efficiently than to the DCM pile. Moreover, the settlement on SDCM pile is less than that on DCM pile and consequently, effected a settlement reduction of about 40%. Therefore, SDCM pile can reduce the intensity of pressure on the surrounding clay

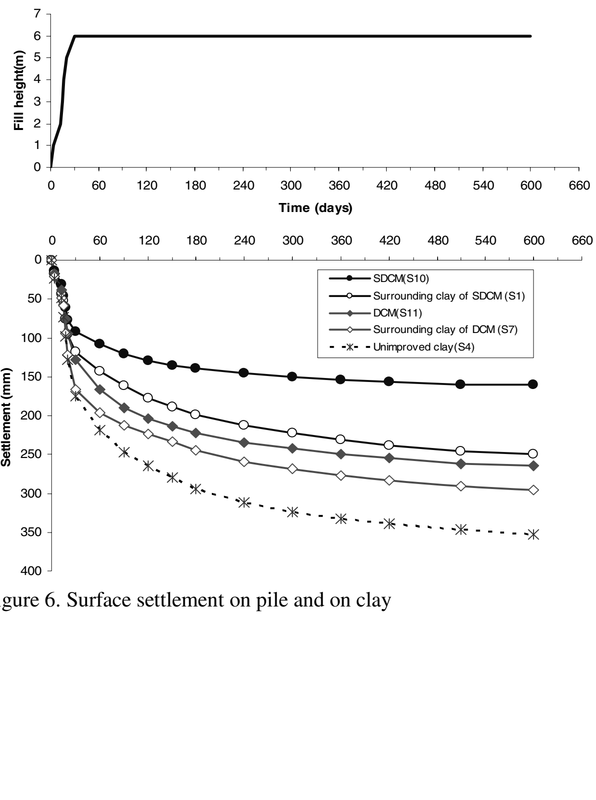

Figure 6. Surface settlement on pile and on clay

and, subsequently, reduce the magnitude of settlement and increase the bearing capacity of the improved foundation.

4 CONCLUSIONS

Full scale test embankments were constructed on improved Bangkok clay, The method of soft clay foundation improvement included prefabricated vertical drain (PVD) only, PVD with heat (Thermo-PVD), deep cement mixing (DCM) and stiffened DCM (SDCM). As expected, the settlement rate and magnitude for Thermo-PVD were greater than for PVD only. In particular, the rate of settlements of Thermo-PVD were 3 times faster than PVD only. Moreover, the SDCM reduced the settlements by as much as 40% compared to DCM piles. Therefore, these innovative soft ground, treatment involving Thermo-PVD and SDCM methods are viable techniques for future applications.

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