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Recent developments of ground improvement with pvd on soft Bangkok clay

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ABSTRACT: The soft Bangkok clay foundation at the site of the Second Bangkok International Airport (SBIA) and the Second Bangkok Chonburi Highway Project (SBCH), were improved using PVD. At SBIA, the water content reduction from field measurements were in agreement with the computed values from the consolidation settlements. Employing the SHANSEP technique, there was excellent agreement between measured and predicted undrained shear strength. Moreover, the actual required discharge capacity has been successfully back-calculated. At the SBCH, a one-dimensional FEM software capable of calculating the consolidation of multi-layered soil, called PVD-SD, was also used for settlement prediction. The PVD-SD method demonstrated slight overprediction. Electro-osmotic (EO) consolidation involves application of direct current electricity through electro-conductive PVDs as electrodes. Due to EO consolidation, significant increase in shear strength and faster rate of settlement were achieved at shorter time. Vacuum preloading is imposed by reducing the pore pressure in the clay through the application of vacuum pressures. The vacuum preloading with PVD increased the rate of settlement by 60% and reduced the preloading period by 4 months.

1 INTRODUCTION

Because of its low permeability, the consolidation settlements of soft clays takes a long time to complete. To shorten the consolidation time, prefabricated vertical drains (PVD) are installed together with preloading by surcharge embankment. PVDs are artificially-created drainage paths which are inserted into the soft clay subsoil. Thus, the porewater squeezed out during the consolidation of the clay due to the hydraulic gradients created by the preloading, can flow faster in the horizontal direction towards the PVDs taking advantage of higher horizontal permeability of the clay. Subsequently, these pore water can flow freely along the PVDs vertically toward the permeable layers. Therefore, the PVD installation reduces the length of the drainage path and, consequently, accelerates the consolidation process and allows the clay to gain rapid strength increase.

The PVD was first investigated for its effectiveness in improving the soft Bangkok clay in subsiding environment (Bergado et al. 1988). Later, the research direction extended into back-analyses of design parameters (Bergado et al. 1991, 1992, 1996a), numerical analysis and modeling (Bergado & Long 1994, Chai et al. 1995), model tests, performance, evaluation of PVD types (Bergado 1996a), and evaluation and development of specification criteria (Bergado et al. 1996b,c). In 1992, the first major project using PVD in the Central Plain of Thailand was finally realized when PVD was utilized in the State Railway of Thailand (SRT) route from Klong 19 to Kaengkhoi, Saraburi. Currently, PVDs are being used for the Second Bangkok Chonburi Highway (SBCH) and the Outer Bangkok Ring Road (OBRR). In the Second Bangkok International Airport (SBIA), the PVD has been studied by full scale field embankments and the PVD ground improvement is being implemented. Moreover, vacuum assisted preloading has been studied at the SBIA site in order to reduce the preloading period, reduce the amount of sand surcharge, and eliminate embankment stability problem. In addition, the consolidation period can be further reduced by using electro-osmotic consolidation in conjunction with PVD installation. Electro-osmosis is the process wherein positively charge ions move from the anode to the cathode carrying hydrated water with them upon the application of direct electric current.

2 SITE AND SOIL CONDITIONS

The Bangkok subsoils, part of the larger Chao Phraya Plain, consist of alternate layers of sand,

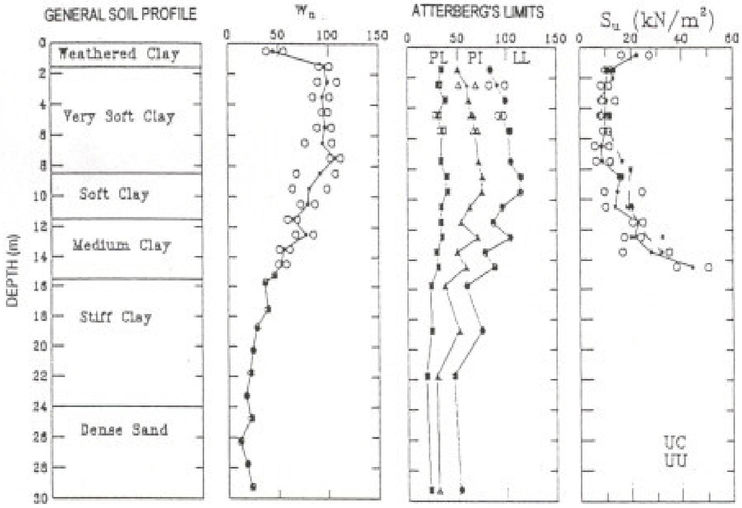

Fig. 1 Generalized Soil Profile and Properties

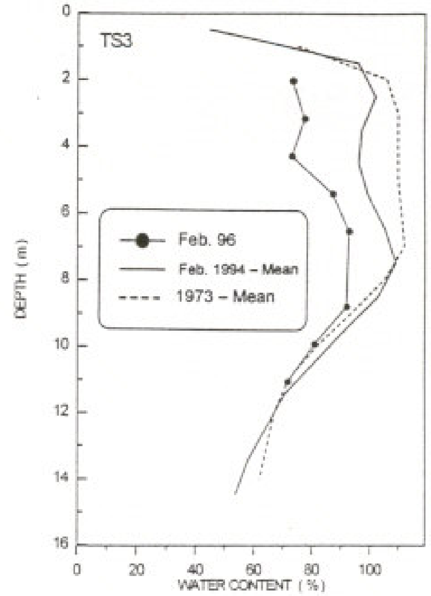

Fig. 2 Water Contents Before and After Preloading with PVD for TS3

gravel and clay. The underlying profile of the bedrock is still undetermined, but its level is known to be between 550 to 2000 m below the ground surface.

The test site is located approximately 30 km east of the capital city of Bangkok. The generalized soil profile and soil properties are shown in Figure 1. The soil profile is relatively uniform consisting of a thin weathered crust (2 m thick) overlying very soft to soft clay approximately 10 m thick. Underlying the soft clay is a medium clay layer of about 4 m thick followed by a stiff clay layer extending down to 22 m depth which is in turn underlain by a layer of dense sand. The profiles of soil strength determined by laboratory tests are also shown.

The natural water contents are reasonably uniform across the site, and lie close to the liquid limit between depths of 2 and 16 m. Most of the Atterberg values lie above the A-line on the plasticity chart, confirming the high plasticity of the Bangkok clay. The groundwater varies at depths of 0.5 to 1.0 m.

3 PVD AT THE SBIA

Three full scale test embankments (TS1, TS2, TS3) were constructed in stages on PVD improved soft Bangkok clay at SBIA site with PVD spacing of 1.5, 1.2 and 1.0 m, respectively, in square pattern (Bergado et al, 1997). All PVDs were installed to 12 m depth. Three PVD models were installed in the test embankments, namely: Flodrain in TS1, Castle Board in TS2, and Mebra drain in TS3. After the PVD installation, the thickness of the sand drainage blanket was increased to 1.5 m. Then, clayey sand was used to raise the embankment to 4.2 m (i.e., 75 kPa of surcharge) in stages.

The test embankments were 40 x 40 m in plan dimensions with 3H:1V side slopes and a finished height of 4.2 m. For TS3, a berm width of 5 m and 1.5 m high was included. Construction took 9 months to complete. The fill material was compacted to an average bulk unit weight of 18 kN/m^3.

Surface and subsurface settlement gauges were installed near the center of the test embankment. The subsurface settlement gauges and the piezometers were installed at 2 m interval.

The results show consistent patterns in settlements, pore pressures, and lateral movements. The settlement was fastest in TS3 (1.0 m PVD spacing) than in TS2 (1.2 m spacing) and TS2 was faster than TS1 (1.5 m PVD spacing). The lateral deformation-settlement pattern was similar for all 3 embankments.

Figure 2 illustrates the reduction of water content with depth for test embankment TS3 after 660 days of preloading (February 1996) compared to mean values measured in February 1994. Previous values from 1973 study by Moh & Woo (1987) are included as dotted lines. The reduction in water content at TS3 is more than 20% which agreed with the back-calculated values from settlement data. The increase in undrained shear strength was predicted by SHANSEP technique (Ladd 1991). The predicted increase are indicated by solid lines in Figure 3. The corrected undrained shear strengths measured by field vane shear tests in February 1994, May 1995 and March 1996 are also plotted for comparison. There is excellent agreement between the measured and predicted increase in undrained shear strength due to preconsolidation and drainage by PVD.

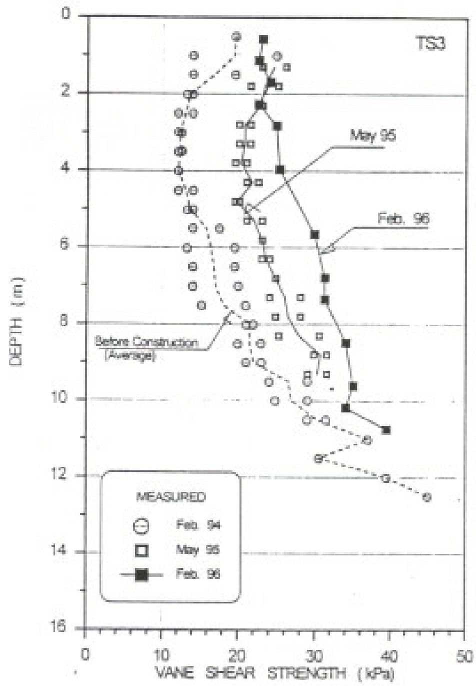

Fig. 3 Field Vane Shear Strength Measured in Embankment TS3

Assuming $K_h/K_s = 5$ and using $C_h = 3$ m^2/yr, the C_h versus discharge capacity, q_w, can be back-calculated based on the concepts of Asaoka (1978) for the three test embankments as shown in Fig. 4. The back-calculated q_w ranged from 30 to 100 m^3/yr. Assuming $K_h/K_s = 5$, $d_s/d_m = 2$, and $q_w = 30$ m^3/yr, C_h values were back-calculated and were in agreement with the corresponding values from piezocone tests as shown in Fig. 5. The results of the 1983 study are also plotted for comparison (Bergado et al, 1996a). The accuracy of the back-calculated parameters depends on the limitation of the Asaoka (1978) method as well as the assumption of radial consolidation.

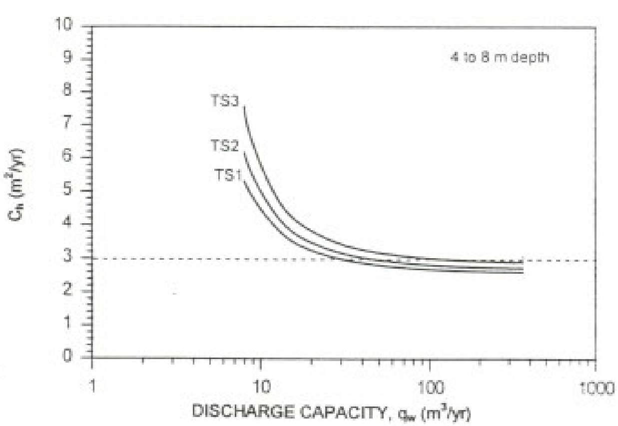

Fig. 4 Comparison of C_h-q_w Relations of Three Test Embankments TS1, TS2 and TS3 Using the Same Value of Smear Ratio, $K_h/K_s = 5$

4 PVD PERFORMANCE AT THE SBCH

The PVD performances at Sections 2A/2 and 2B/1 of SBCH which have the thickest layer of very soft to soft clay and having maximum settlements throughout the highway, were evaluated. The field settlements as well as the fill height were compared with those proposed and predicted by the designers (Bergado et al, 1999).

The settlements predicted by Asaoka's method (Asaoka 1978) represented the settlement of the whole stratum (improved and unimproved layers), as it is based upon the monitored surface settlement record. At the final stage of loading, the subsoil at all sections has gone through about 90% or more degree of consolidation. PVD-SD is a one-dimensional FEM software capable of calculating the consolidation of multi-layered soil. PVD-SD calculations indicate that most of the settlement took place at 2 to 12 m depth, corresponding to the zone of very soft to soft clay.

Figure 6 shows a comparison of the settlements predicted by the different methods with the observed data for Section 2B/1. The time-settlement plot predicted on the basis of Asaoka's method (Asaoka 1978) shows that the calculated settlements were in excellent agreement with the observed data. The PVD-SD method also yielded very good predictions whereas the one-dimensional method based on Terzaghi's theory slightly overpredicted the settlements.

5 VACUUM PRELOADING

The scarcity of sand to be used as surcharge fill has led to the proposal to explore a combined vacuum preload and surcharge technique. The idea is to reduce the fill height and shorten the time of preloading. Instead of increasing the effective stress in the soil mass by increasing the total stress by

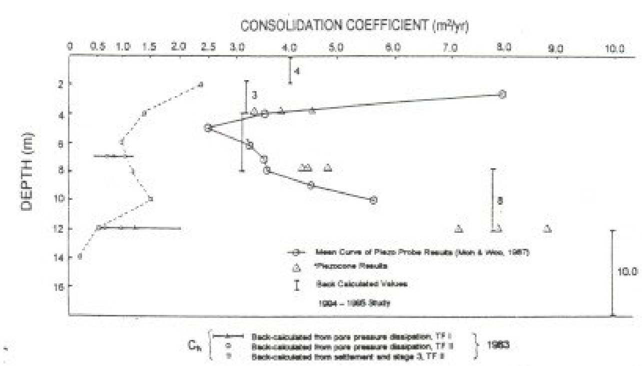

Fig. 5 Comparison of C_h Values

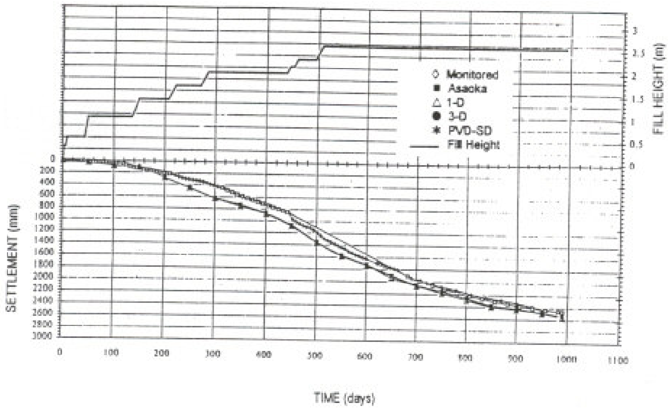

Fig. 6 Time-Settlement Plot using Different Methods at Section 2B/1, SBCH Project

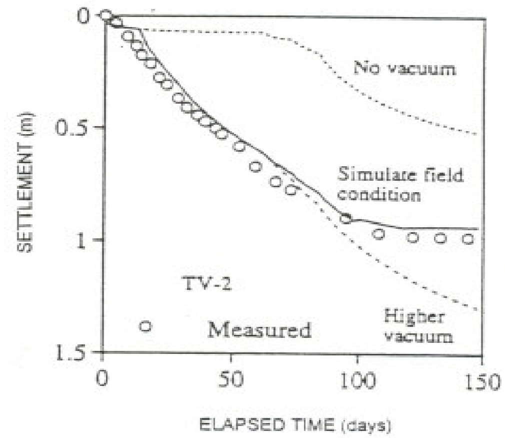

Fig. 7 Calculated and Measured Settlements for Embankment 2 (TV-2)

means of conventional mechanical surcharging, vacuum assisted consolidation preloads the soil by reducing the pore pressure while maintaining constant total stress.

Two additional 40 x 40 m embankments were constructed at the SBIA site close to the previous PVD embankments with a platform of 0.3 and 0.8 m sandfill for Embankments 1 and 2, respectively. For Embankment 1 (TV1), 15 m long PVD was used in conjunction with hypernet and nonwoven geotextiles drainage system. For Embankment 2 (TV2), 12 m long PVD was used together with corrugated pipe and nonwoven geotextile drainage system. PVD spacing was at 1.0 m in a triangular pattern for both embankments.

A water and airtight very low density (VLDPE) geomembrane was placed on top of the drainage layer. To maintain airtightness, the ends of the liner were placed on the bottom of a perimeter trench and covered with 300 mm layer of sand-bentonite mix and water. A vacuum pump with a capacity of 100 m^3/hr and pressure of –70 kPa was installed for each embankment. After applying vacuum pressure for 45 days, the embankments were raised in stages up to a height of 2.50 m. The pumps were run continuously for 5 months (Bergado et al, 1998).

Figure 7 compares the FEM results with the corresponding measured data assuming no vacuum pressure, with vacuum pressure that simulated the field conditions, and with higher vacuum pressure (-60 kPa) for Embankment 2. Similar trends of results were also observed for Embankment 1. The results indicated that even with PVD instal-lation, high vacuum needs to be maintained for 4 to 5 months to achieve higher degree of consolidation.

The final settlement of TV1 and TV2 were 0.74 and 0.96 m, respectively. The performance of TV2 when compared to previous studies using conventional sand surcharging, as shown in Figure 8, produced an acceleration in the rate of settlement by about 60% and a reduction in the period of preloading by about 4 months.

The major difficulty experienced with this type of preloading is the maintenance of vacuum pressure. Even though a vacuum preloading of 75 kPa was anticipated, the actual measured values seem to indicate an efficiency of only 40 to 50% equivalent to a surcharge pressure of 35 to 40 kPa.

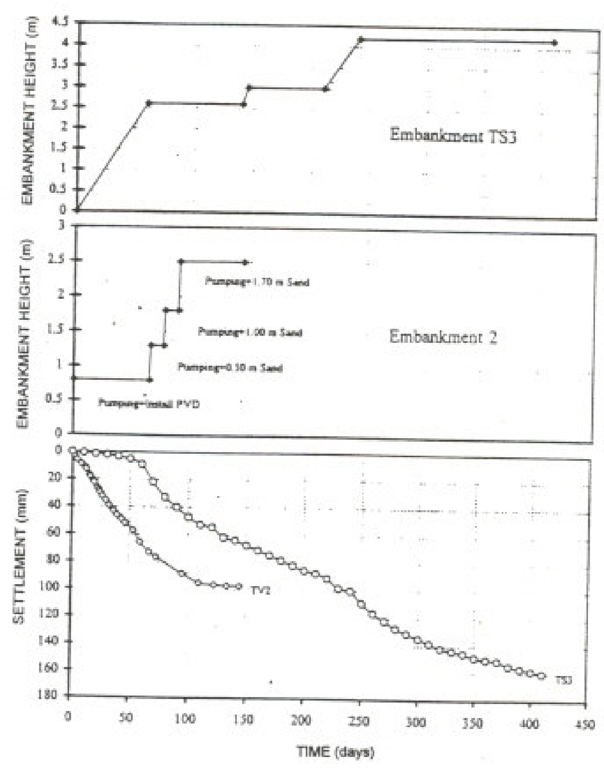

Fig. 8 Comparison of Maximum Surface Settlement Between Embankment 2 and Previous Embankment TS3 at SBIA Site

Electro-osmosis (EO) is the process wherein positively charged free water in a clay-water system moves from the anode to the cathode. Upon application of a direct current, cations in the diffused double-layer of water moves toward the cathode to gain electrons and thereby become discharged. As the cations move, they carry with them water so that there is a new movement of water toward the cathode. Consolidation will result if water is removed at the cathode but not replaced at the anode.

Studies on the effect of electro-osmotic consolidation on soft Bangkok clay were performed in the laboratory. Two types of electro-conductive drains made from common prefabricated vertical drains (PVD) were used. These consist of copper electrodes made by inserting 2 mm diameter copper rods into the drain core, and carbon electrodes made by wrapping the drains with carbon fibers. The samples were reconstituted and tested in a 300 mm high having 300 mm diameter small cylinder cell (Abiera et al, 1999; Bergado et al, 2000). Two holes at the top and bottom cap, spaced 200 mm apart, were provided for PVD installation. Vertical load was applied on the top cap through a loading piston. Reconstituted pressure and applied vertical stress was maintained at 5 kPa coupled with 60 and 120 V/m voltage gradients. These voltage gradients were obtained from previous investigators (Abiera et al, 1999; Bergado et al, 1998). Polarity reversal was done every 24 hours. All tests were carried out until 90% consolidation was achieved (Bergado et al, 2000). The initial water content, liquid limit and plastic limit of the soil specimen were 97%, 96% and 33%, respectively. The pH, cation exchange capacity (CEC), and total dissolved salts (TDS) were, respectively, 6.3, 46.85 meq/100g, and 4050 ppm.

The variation of settlement against time and the variation of shear strength across the drains are shown in Figures 9 and 10, respectively. The shear strengths were measured by customized miniature vane shear apparatus. Larger settlements and higher shear strength were obtained upon application of electro-osmotic consolidation compared to using ordinary drains. Moreover, the carbon electrodes displayed better results compared to copper electrodes in both 60 and 120 V/m voltage gradients. The shear strength between the anode and the cathode were almost equal indicating the effectiveness of 24-hour polarity reversal. However, the shear strengths in-between the cathode/anode locations can be lower.

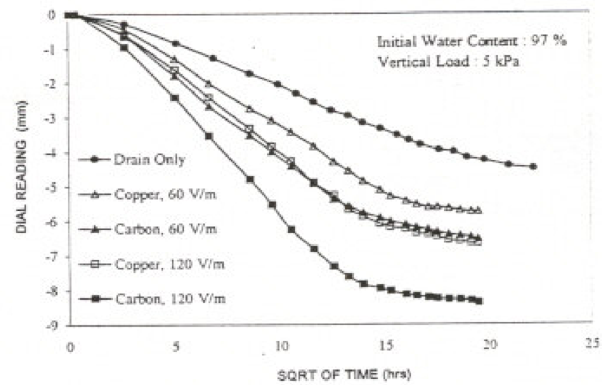

Fig. 9 Variation of Settlement with Time with and without Electro-osmotic Consolidation using Reconstituted Clay Samples

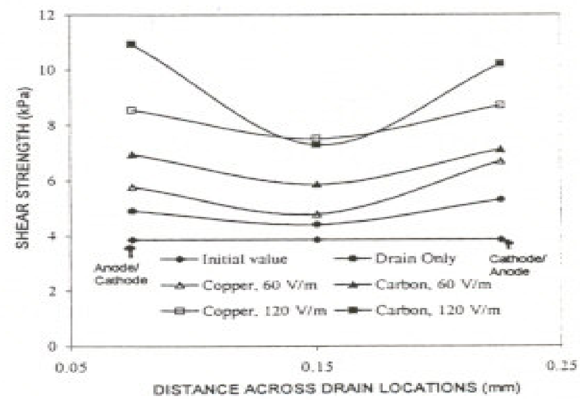

Fig. 10 Variation of Shear Strengths for Recons-tituted Sample (Small Cylinder Cell)

7 CONCLUSIONS

Three full scale test embankments were constructed in stages on soft Bangkok clay at the Second Bangkok International Airport (SBIA) with prefabricated vertical drains (PVD) installed to 12 m depth in a square pattern. The water content reductions from field measurements were in good agreement with the computed values from consolidation settlements. The undrained shear strength with depth as measured in the field is in agreement with the values calculated from the SHANSEP technique due to preconsolidation and drainage. The back-calculated actual discharge capacity, q_w, for the three test embankments ranged from 30 to 100 m^3/yr. The back-calculated C_h values agreed with the corresponding results from piezocone tests.

The PVD performance was also evaluated at selected sections of the Second Bangkok Chonburi Highway (SBCH) Project. The rate and amount of settlement predicted by Asaoka's method proved to be in excellent agreement with the observed values.

The settlements predicted by the one-dimensional FEM computer program PVD-SD proved to be in reasonable agreement with the measured values.

Two additional embankments were constructed at SBIA to study the effect of vacuum preloading in combination with reduced amount of sand surcharging. The final settlement of TV1 and TV2 were 0.74 and 0.96 m, respectively. The performance of TV2 when compared to previous studies using conventional sand surcharging showed an acceleration in the rate of settlement by about 60% and a reduction in the period of preloading by about 4 months.

Electro-osmotic consolidation under 60 and 120 V/m voltage gradient was performed on reconstituted soft Bangkok clay using drains modified by adding copper and carbon electrodes. Tests indicated larger settlements and higher shear strength for both electro-conductive drains compared to ordinary drains. However, the carbon electrodes displayed better results compared to copper electrodes in both voltage gradients. Polarity reversal every 24 hours proved to be effective producing almost equal shear strength between the anode and the cathode.

REFERENCES

Abiera, H.O., Miura, N., Bergado, D.T. & Nomura, T. 1999. Effects of using electro-conductive PVD in the consolidation of reconsti-tuted Ariake Clay. *Geotech. Eng'g. Journals*, Vol. 30, No. 2, pp. 67-84.

Asaoka, A. 1978. Observational procedure for settlement prediction. *Soils and Foundations*, Vol. 18, No. 4, pp. 87-101.

Bergado, D. T., Miura, N., Singh, N. & Panichayatum, B. 1988. Improvement of soft Bangkok clay using vertical band drains based on full scale test. *Proc. of the Intl. Conf. on Eng'g Problems of Regional Soils*, Beijing, China, pp. 379-384.

Bergado, D. T., Asakami, H., Alfaro, M.C. & Balasubramaniam, A.S. 1991. Smear effects of vertical drains on soft Bangkok clay. *ASCE Journal of Geotech. Eng'g. Div.*, Vol. 117, No. 10, pp. 1509-1529.

Bergado, D. T. , Enriquez, A. S., Casan, L., Alfaro, M. C. & Balasubramaniam, A. S. 1992. Inverse analysis of geotechnical parameters on improved soft Bangkok clay. *ASCE Journal of Geotech. Eng'g. Div.*, Vol. 118, No. 7, pp. 1012-1030.

Bergado, D. T. & Long, P. V. 1984. Numerical analysis of embankment on subsiding ground improved by vertical drains and granular piles, *Proc. 13th Intl.Conf. Soil Mech. Found. Eng'g.*, New Delhi, India, Vol. 4, pp. 1361-1366.

Bergado, D. T., Long, P. V. & Balasubramaniam, A. S. 1996a. Compressibility and flow parameters form PVD improved soft Bangkok clay. *Geotech. Eng'g. Journal*, Vol. 27, No. 1, pp. 1-20.

Bergado, D. T., Mannivannan, R. & Balasubramaniam, A. S. 1996b. Proposed criteria for discharge capacity of prefabricated vertical drain. *Geotextiles and Geomembranes*, Vol. 14, pp. 481-505.

Bergado, D.T., Mannivannan, R. & Balasubramaniam, A.S. 1996c. Filtration criteria of prefabricated vertical drains filter jackets on soft Bangkok clay. *Geosynthetics Intl.*, Vol. 3, No. 1, pp. 63-83.

Bergado, D.T., Balasubramaniam, A.S., Fannin, R.J., Anderson, L.R. & Holtz, R.D. 1997. Full scale field test of prefabricated vertical drain (PVD) on soft Bangkok clay and subsiding environment.*Ground Improvement Developments 1987-97 (GeoLogan '97)*, Geotech. Special Publ. No. 69, ASCE, New York, U.S.A.

Bergado, D.T., Chai, J.C., Miura, N. & Balasubramaniam, A.S. 1998. PVD improvement of soft Bangkok clay with combined vacuum and reduced sand embankment preloading. *Geotech. Eng'g. Journal*, Vol. 29, No. 1, pp. 95-122.

Bergado, D.T., Balasubramaniam, A.S., Chishti, I.A., Ruenkrairergsa, T. & Taesiri, Y. 1999. Evaluation of the PVD performance at the Second Bangkok Chonburi Project. *Lowland Tech. Intl.*, Vol. 1, No. 2, pp. 55-75.

Bergado, D.T., Balasubramaniam, A.S., Patawaran, M.A.B. & Kwunpreuk, W. 2000. Electro-osmotic consolidation of soft Bangkok clay with prefabricated drains. *Ground Improvement*, Vol. 4 (in press).

Chai, J.C., Miura, N. & Bergado, D. T. 1995. Behavior of PVD improved ground under embankment loading. *Soils and Foundations*, Vol. 35, No. 4, pp. 49-61.

Ladd, C. C. 1991. Stability evaluation during staged construction. *ASCE Journal of Geotech. Eng'g. Div.*, Vol. 117, No. 4, pp. 540-615.

Moh, Z. C. & Woo. S. M. 1987. Preconsolidation of Bangkok clay by non-displacement sand drains and surcharge. *Proc. 9th Southeast Asian Geotechnical Conference*, Bangkok, Thailand, Vol. 1, pp. 8-171 to 8-184.