Numerical Simulations and Full Scale Behavior of SDCM and DCM Piles on Soft Bangkok Clay

P. Voottipruex, D.T. Bergado, T. Suksawat, P. Jamsawang

Abstract. A new kind of reinforced Deep Cement Mixing (DCM) pile, namely: Stiffened Deep Cement Mixing (SDCM) pile is introduced to mitigate the problems due to the low flexural resistance, lack of quality control in the field and unexpected failure of DCM pile. The SDCM pile consists of DCM pile reinforced with precast concrete core pile. Previously, the full scale embankment loading test on soft Bangkok clay improved by SDCM and DCM piles was successfully conducted and monitored. The parameters were also derived from an earlier full scale load tests to failures and subsequent simulations. To continue the study on the behavior of SDCM and DCM piles, the 3D finite element simulations and parametric study have been done. The simulation results of the full scale embankment loading test indicated that the surface settlements decreased with increasing lengths of the concrete core piles from 4 to 6 m but slightly reduced from 6 to 7 m as well as slightly decreased with increasing sectional areas in the SDCM piles. In addition, the lateral movements of the embankment decreased by increasing the lengths (longer than 4 m) and, to a lesser degree, the sectional areas of the concrete core piles in the SDCM piles. The results of the numerical simulations closely agreed with the observed data from full scale field tests and successfully verified the parameters affecting the performances and behavior of both SDCM and DCM piles.

Keywords: SDCM piles, DCM piles, bearing capacity, lateral load, settlement, lateral movement, piled embankment.

1. Introduction

Although DCM pile has many advantages with various applications, failure caused by pile failure can occur especially when subjected to the lateral loads. Moreover, the unexpected lower strength than the design commonly occurs due to lack of quality control during construction. Thus, DCM pile still fails by pile failure mode which is lower than the soil failure mode particularly at the top of DCM pile due to low strength and stiffness as shown in Fig. 1 (a). In addition, Fig. 1 (b) shows the testing results of DCM pile on the soft Bangkok clay by Petchgate *et al.* (2003). About half of DCM piles failed by pile failure instead of soil failure. Consequently, the bearing capacity of DCM pile can be lower than the design load of 10 tons due to pile failure. Both pile and soil failures are illustrated in Fig. 1a.

To mitigate the above-mentioned problem, a new kind of composite pile named Stiffened DCM (SDCM) pile is introduced. This composite pile is composed of an inner precast concrete pile hereinafter called concrete core pile and an external DCM pile socket, where the high strength concrete pile is designed to bear the load, and DCM pile socket acts to transfer the axial force into the surrounding soil by skin friction.

The acceptance of numerical simulations in geotechnical problems is growing and finite element methods are increasingly used in the design of pile foundations. In this study, the full scale tests results were further simulated in order to study the parameters that affect the behavior of both the SDCM and DCM piles under the axial compression and lateral pile load as well as embankment load tests. Subsequently, the confirmed and verified parameters were used in the numerical experiments. Previously, the results of laboratory investigations of SDCM and their numerical simulations by Jamsawang *et al.* (2008) yielded useful parameters. The previous results served as the basis for the full scale pile load and embankment tests. Subsequently, numerical simulations were performed by Suksawat (2009) to back-calculate the strength parameters as well as to perform parametric study. Consequently, the results are presented in this paper.

2. Stiffened Deep Cement Mixed (SDCM) Piles

Stiffened Deep Cement Mixed (SDCM) piles are a composite structure of concrete piles and deep cement mixed piles combining the advantages of both components as shown in Fig. 2a,b. A pre-stressed concrete stiffer core is installed by inserting into the center of a DCM pile immedi-

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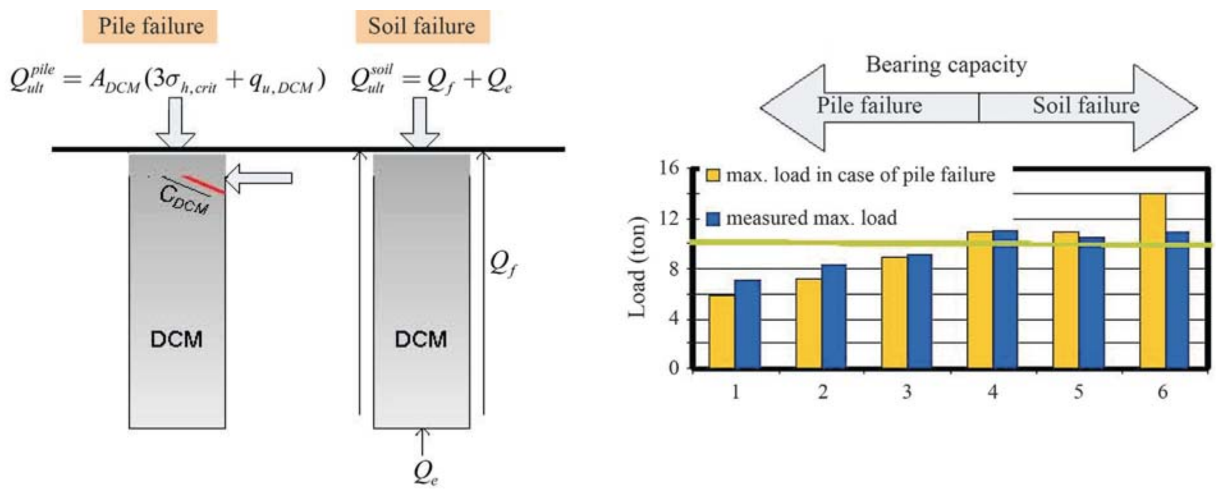

Figure 1 - Low quality of DCM piles on Soft Bangkok Clay (Petchgate *et al.*, 2003).

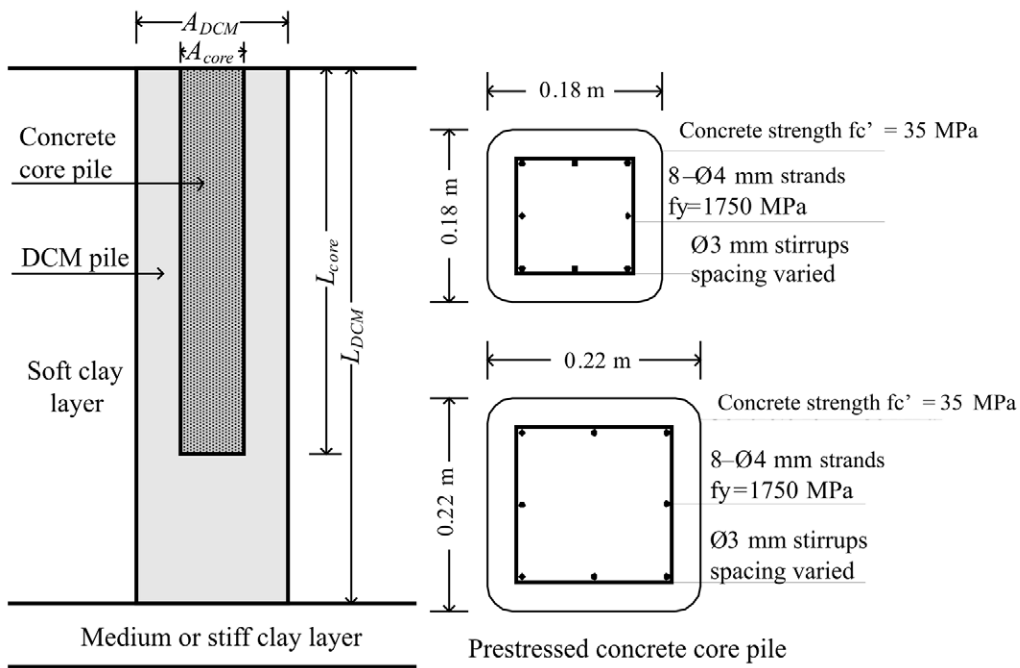

Figure 2 - (a) Schematic of SDCM pile, (b) Details of prestressed concrete core piles.

ately after the construction of wet mixing DCM pile. The two parts of the composite piles work together by supporting and transferring the vertical load effectively to the DCM pile and to the surrounding soil. In the SDCM pile, the DCM pile forms the surrounding outer layer supporting the concrete core pile increasing its stiffness and resisting compressive stress along the pile shaft. The dimensions of the two units should be such that both work together effectively and mobilize the full strength of the surrounding clayey soil. This novel method of improving the strength of DCM pile has been given different names by different researchers such as concrete cored DCM pile (Dong *et al.*, 2004), composite DMM column (Zheng & Gu, 2005) and stiffened deep cement mixed (SDCM) column method (Wu *et al.*, 2005).

2.1. DCM pile

The DCM pile is used as the socket pile in order to carry and transfer the load from concrete core pile to the surrounding soil. In this study, the DCM pile was constructed by wet mixing with 0.60 m diameter and 7.00 m length.

2.2. Concrete core pile

The Stiffened Deep Cement Mixing (SDCM) pile need some material to enhance its stiffness like steel pile, timber and concrete pile etc. The prestressed concrete pile is more suitable than the other materials because it is cheaper than the steel pile and easier to manufacture. Moreover, the quality of prestressed concrete is better when comparing to the timber piles. Thus, the prestressed concrete core pile was proposed to bear the axial load in compression pile load test and resist lateral loads when subjected to the horizontal loads in SDCM pile.

2.3. Interface friction

The interface friction or adhesion means the ratio of the adhesive strength, τ_u, to the unconfined compression strength, q_u, of the clay cement. This value represents the frictional or adhesion resistance per unit cement soil strength provided on per unit side area of the concrete core pile. It is denoted by R_{inter} and calculated by following equation:

$$R_{inter} = \frac{\tau_u}{q_u} \tag{1}$$

where τ_u is the adhesive strength that can be calculated from the ultimate frictional strength P_u divided by surface area of the stiffer core using the following equation:

$$\tau_u = \frac{P_u}{AL} \tag{2}$$

where A is the cylindrical surface area and L is the length of concrete core pile.

Many researchers have reported that the R_{inter} varies from 0.348 to 0.426 with an average value of 0.4 (Wu *et al.*, 2005 and Bhandari, 2006).

3. Project Site and Subsoil Profile

The full scale axial and lateral pile load tests were performed by Shinwuttiwong (2007) and Jamsawang (2008) and the full scale embankment load test was conducted by Jamsawang (2008) within the campus of Asian Institute of Technology (AIT). The site is situated in the central plains of Thailand famous for its thick layer deposit of soft Bangkok clay. The foundation soils and their properties at the site are shown in Fig. 3. The uppermost 2.0 m thick layer is the weathered crust, which is underlain by 6.0 m thick soft to medium stiff clay layer. A stiff clay layer is found at the depth of 8.0 m from the surface. The undrained shear strength of the soft clay obtained the from field vane test was 20 kPa and the strength of the stiff clay layer below the depth of 8.0 m from the surface is more than 40 kPa (Bergado *et al.*, 1990). Other parameters are shown in Table 1.

The strength of the concrete piles was found to be 35 MPa. Two lengths of concrete core piles were used in the field test, namely: 4.0 m and 6.0 m. However, for the numerical simulation the length of the concrete pile was varied from 1.00 m to 7.00 m with 1.0 m increase to evaluate the effect of the lengths of the core pile on the capacity of the SDCM pile. The Mohr-Coulomb model was recommended to simulate for mass concrete core pile instead of linear elastic model because its stiffness can be overesti-

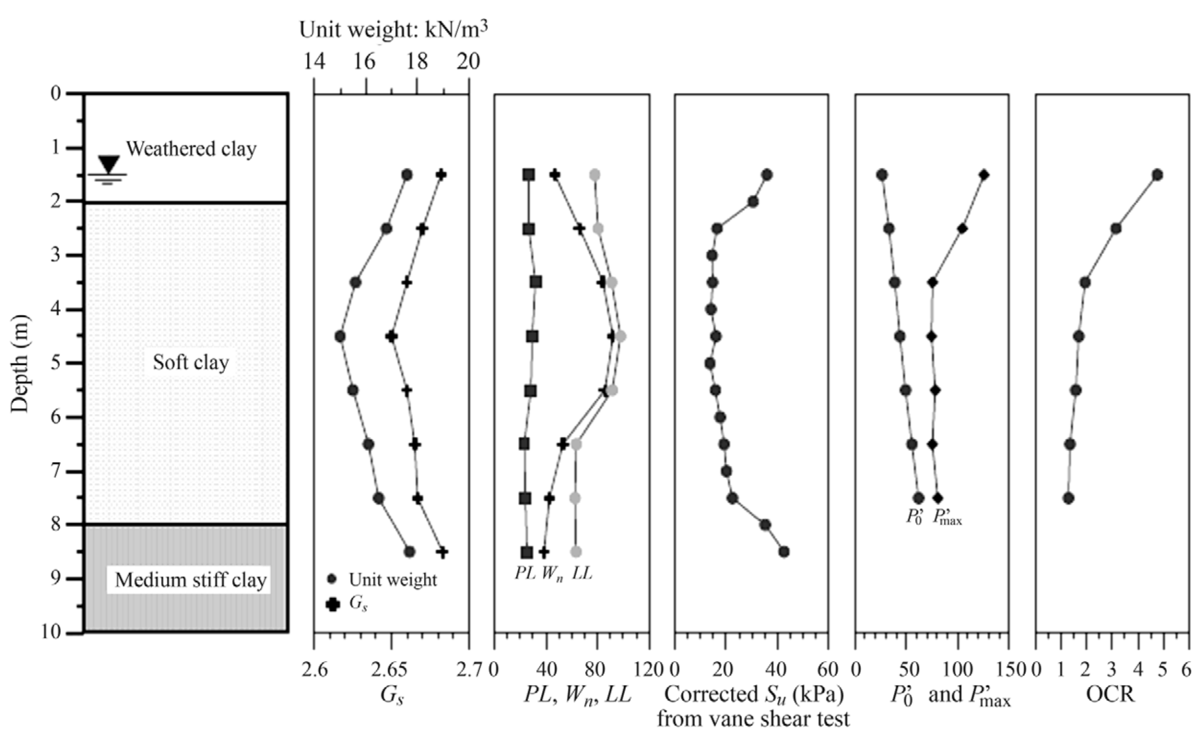

Figure 3 - Subsoil profile within the campus of AIT.

Table 1 - Soil models and parameters used in 3D FEM simulation.

Materials	Depth (m)	Model	γ (kN/m^3)	Material behavior	E'_{ref} (kPa)	ν	λ^*	κ^*	C' (kPa)	ϕ' (°)	k_x (m/day)	OCR	Tensile strength (kPa)
Subsoil													
Weathered crust	0-2.0	MCM	17	Undrained	2500	0.25			10	23	$1x10^{-3}$		
Soft clay	2.0-8.0	SSM	15	Undrained			0.10	0.02	2	23	$4x10^{-4}$	1.5	
Medium stiff clay	8.0-10.0	MCM	18	Undrained	5000	0.25			10	25	$2x10^{-4}$		
Stiff Clay	10.0-30.0	MCM	19	Undrained	9000	0.25			30	26	$4x10^{-4}$		
Foundation													
Concrete core pile		MCM	24	Drained	$2.8x10^7$	0.15			8000	40			5000
DCM pile (with interface elements)		MCM	15	Undrained	30000-60000	0.33			100-300	30	0.012	0-100	
Steel plate		LEM	-	Non-porous	$2.1x10^8$	0.15							

Note: SSM = Soft Soil Model, MCM = Mohr-Coulomb Model, LEM = Linear Elastic Model.

mated if the tensile strain is large enough to crack the concrete (Tand *et al.*, 2008).

4. Full Scale Axial and Lateral Pile Load as Well as Embankment Load Tests

The DCM pile was constructed by jet grouting method employing a jet pressure of 22 kPa and cement of 150 kg/m^3 of soil. The values of unconfined compressive strength of DCM obtained from field specimens ranged from 500 kPa to 1,500 kPa with average value of 900 kPa while the modulus of elasticity ranged from 50,000 kPa to 150,000 kPa with average value of 90,000 kPa indicating the empirical relation of $E_{50} = 100\,q_u$. The full scale pile load test piles consisted of 16 SDCM and 4 DCM piles. For the DCM pile 0.60 m. in diameter and 7.00 m length was used and SDCM with lengths ranging from of 4 and 6 m was utilized. The layout of full scale DCM and SDCM piles shown in Fig. 4 which indicates axial compressive (C), lateral (L) and pullout (P) pile load tests.

4.1. Axial compression pile load test

The axial compression pile tests were conducted on both the DCM and SDCM piles. As shown in Fig. 2b, the concrete core piles consisted of 0.18 m and 0.22 m. square piles. The DCM piles has 0.60 m. diameter. The load was applied increasing at 10 kN interval until pile failure. The bearing capacities of the 0.18 m square core pile with 4.00 m and 6.00 m were 265 kN and 300 kN, respectively, while the corresponding value for 0.22 m. square core pile with 4.00 m and 6.00 m were 275 kN and 315 kN, respectively. The bearing capacities of DCM piles were found to be 200 and 140 kN. The result from full scale pile load tests indicated that both the length and section area of concrete core piles increased the bearing capacities and reduced the settlement of SDCM piles. However, it was demonstrated that length was more dominant than the section area of the concrete core pile. Finally, the bearing capacity of SDCM pile is higher than the DCM pile. The ultimate bearing capacities of all piles were determined according to the failure criterion of Butler &Hoy (1977).

4.2 Lateral pile load test

The full scale lateral pile load tests were also conducted on designated SDCM piles. The 0.18 m and 0.22 m square core piles with 0.60 m DCM diameter were used. The horizontal load was applied depth at -0.30 m at the top of pile with increasing lateral load until pile failure. The maximum lateral load of the 0.18 m square core pile with length of 3.50 m and 5.50 m were 33 kN and 34.5 kN, respectively, while the maximum lateral load of the 0.22 m square core pile with length of 3.50 m and 5.50 m were 44.5 kN and 45.5 kN, respectively. By contrast, the maximum lateral load of DCM piles were only 3.5 and 2.5 kN for DCM L-1 and DCM L-2, respectively. The result indicated that the length of concrete core pile did not affect

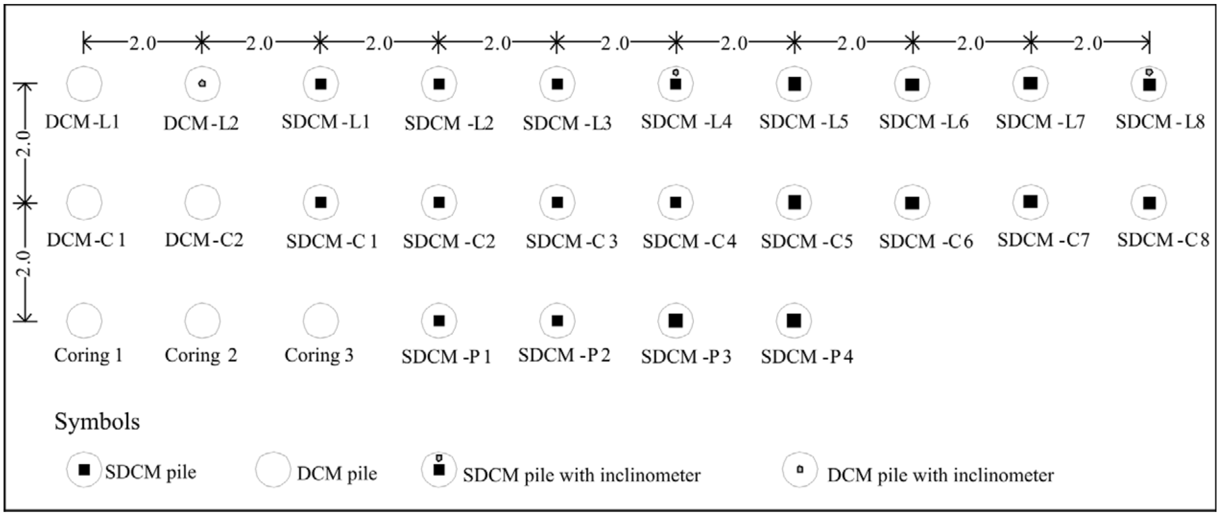

Figure 4 - Pile load test layout.

much the lateral capacity. However, the section area of the concrete core affects much the lateral capacity of the SDCM pile. Both the length and section area were significant factors in reducing the pile displacement when the concrete core pile length was increased from 3.50 m to 5.50 m. Finally, the lateral bearing capacity of SDCM pile was found to be higher than the DCM pile.

4.3. Embankment load test

Jamsawang (2008) and Jamsawang *et al.* (2008, 2009a,b) constructed the full scale test embankment on improved soft Bangkok clay using two different methods namely: stiffened deep cement mixing (SDCM) pile and deep cement mixing (DCM) pile. The DCM pile consisted of 7 m long and 0.6 m in diameter. The objectives of this research work were to investigate ground improvement performances under embankment loading and to verify the related design parameters. Surface settlements and lateral movements were monitored during and after the embankment construction for two years. Figure 5a,b shows the plan layout and side view of the embankment, respectively, together with the DCM and SDCM piles.

5. Procedure of Simulation

5.1. Procedure of numerical simulation of the axial compression and lateral pile load tests

Both axial compression pile load test and lateral pile load test were simulated by PLAXIS 3D Foundation software. The soft soil model (SSM) was used for the soft clay layer and the Mohr-Coulomb model (MCM) was used for the other elements including DCM and SDCM piles. Almost all of element used 15 node wedge element except plate and interface elements used the structural elements. The plate elements are based on the 8 node quadrilateral elements. The interface elements are different from the 8 node quadrilaterals that they have pairs of node with zero thickness instead of single node. The simulation model is indicated in Fig. 6. The soil models together with parameters are tabulated in Table 1.

The initial stage was setup as the in-situ state to generate the initial in-situ stresses. The DCM pile and concrete core pile were then added to the simulation. The excavation stage was simulated by removing 1.00 m of soil around the pile for the axial compression pile load test and 1.5 m of the soil for the lateral pile load test. In the subsequent stages, a plate was used to distribute the load in the axial pile test and the pile cap was added to distribute the load in the lateral pile test.

After the addition of plate in case of axial load test and the pile cap in the lateral load case, the loading of the piles was commenced. For axial compression pile load test, the vertical load was increased in interval of 10 kPa until failure. For the lateral pile load test, the horizontal load was increased in interval of 5 kPa until failure. The programming of stage loading is illustrated in Fig. 7.

5.2. Procedure of numerical simulation for the full embankment load test

The embankment is supported by two types of piles consisting of the 16-SDCM piles and 16-DCM piles (Figs. 5a,b). For the purpose of simulation, the length of concrete core piles in SDCM piles were varied from 3.00 to 7.00 m with varied sectional dimensions from 0.22 x 0.22 to 0.30 x 0.30 m. The embankment discretization model using Plaxis Foundation 3D software (Brinkgreve & Broere, 2006) is illustrated in Fig. 8a,b. The soil parameters and models used in the numerical simulations are tabulated in Table 1. The soft soil model (SSM) was used for the soft clay layer and the Mohr-Coulomb model (MCM) was used for other elements including DCM and SDCM piles. The basic soil elements were represented by 15 node wedge element except the plate and interface elements. The DCM pile was modeled by volume elements that can simulate deformation stresses. The prestressed concrete core pile was modeled as "massive pile" composed of volume elements. The interface elements were modeled as pairs of corresponding nodes with zero distance between each pair as stated in the previous section. Interface elements required strength reduction factor, R_{inter}, for soil strengths mobilized at the interface (see Table 1). The first phase was the initial

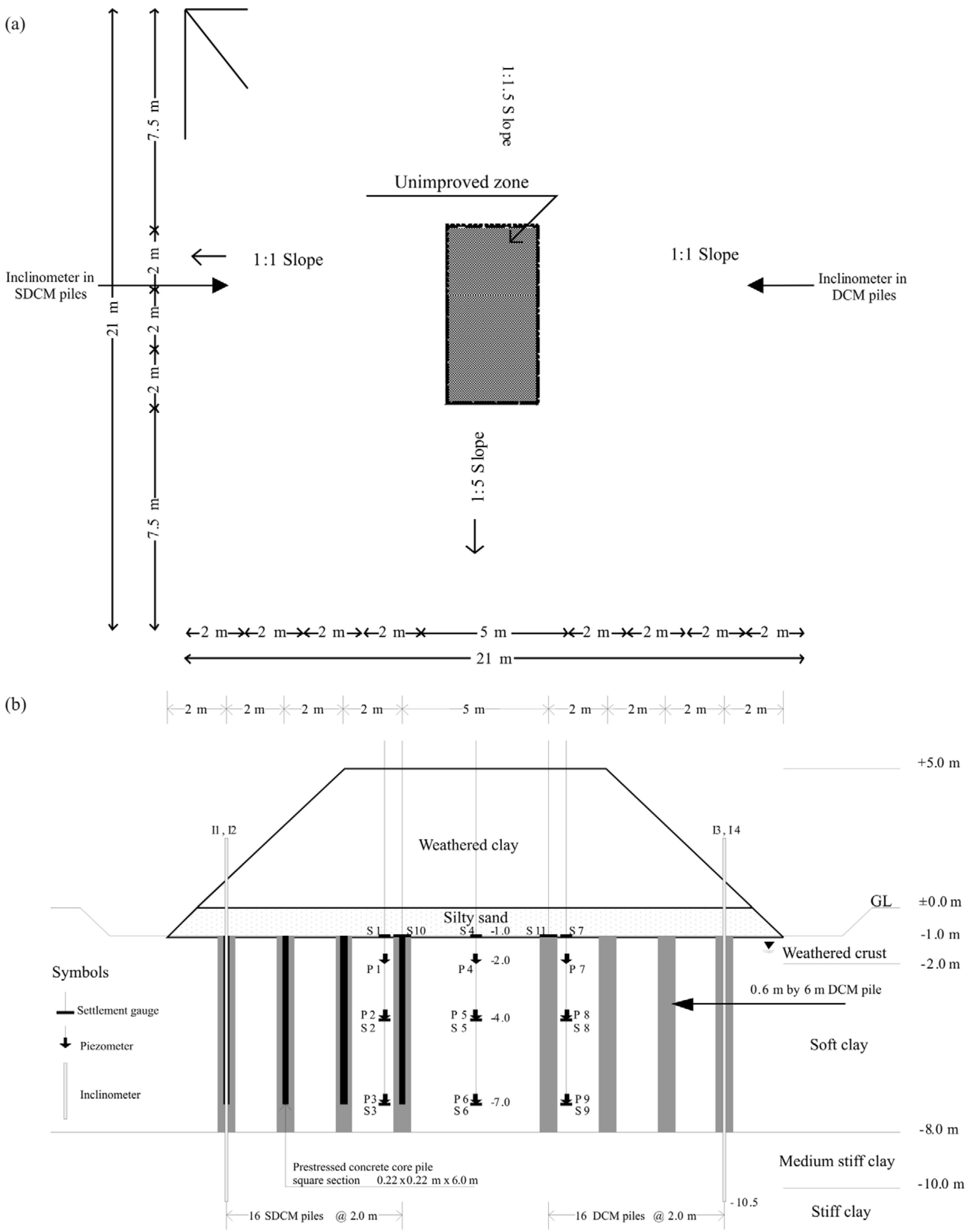

Figure 5 - (a) Top view of the test embankment. (b) Side view and location of instrument of the embankment.

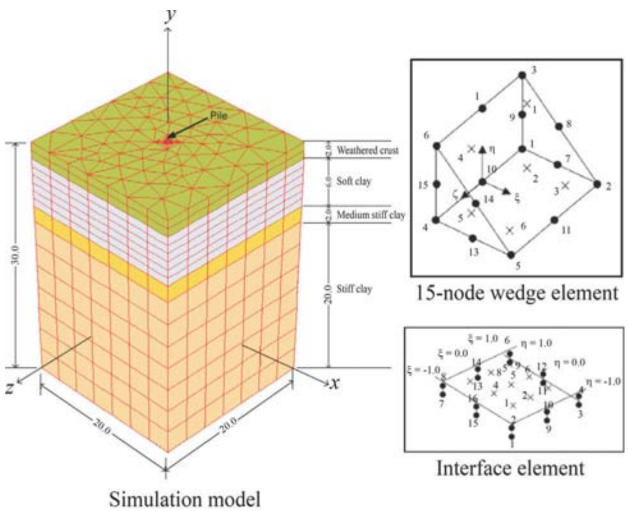

Figure 6 - Axial and lateral pile load test simulation model.

stage that was setup as the in-situ state (k_0 procedure) to generate the initial in-situ stresses. In the second phase, the DCM pile and concrete core pile were installed. Next step was the excavation stage of the uppermost 1.00 m of soil. The subsequent steps consisted of filling the silty sand at the first phase at the base and, subsequently, filled by weathered clay. Afterwards, the surface settlement at the top of SDCM, DCM and surrounding soil were checked after 60, 90, 120, 150, 180, 240, 300, 360, 420, 510 and 600 days, respectively. The details of the stage calculations are illustrated in Fig. 9.

6. Results

6.1. Axial compression pile simulation

As shown in Fig. 4, DCM C-1 and DCM C-2 were constructed for full scale load tests. The appropriate parameters from back analysis for mixture of cement-clay cohe-

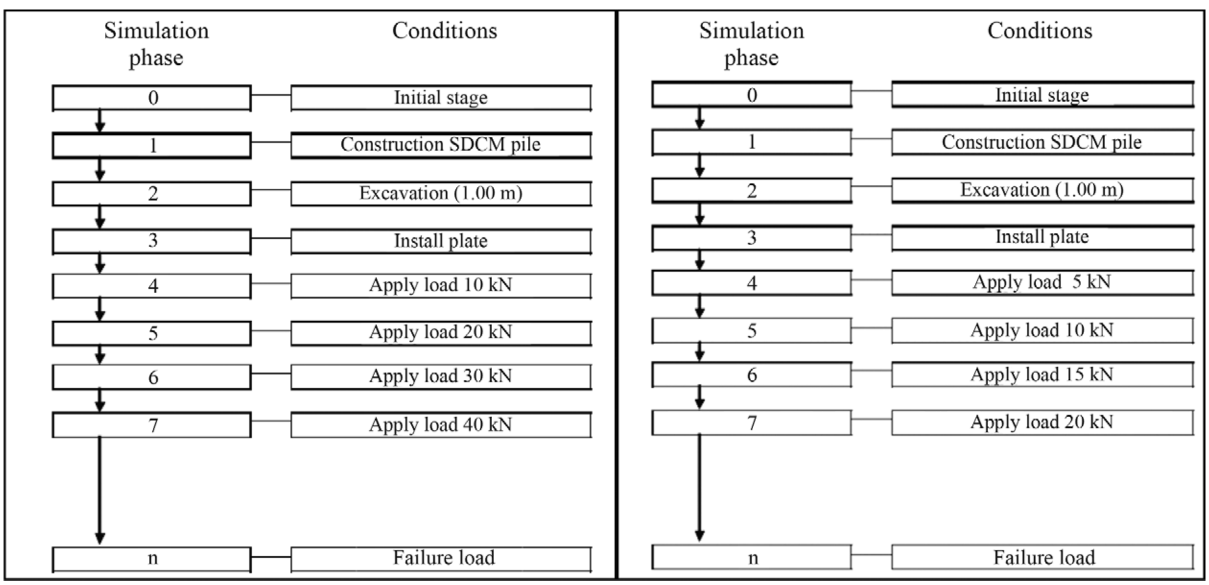

Figure 7 - Finite Element simulation for axial compression and lateral pile load test.

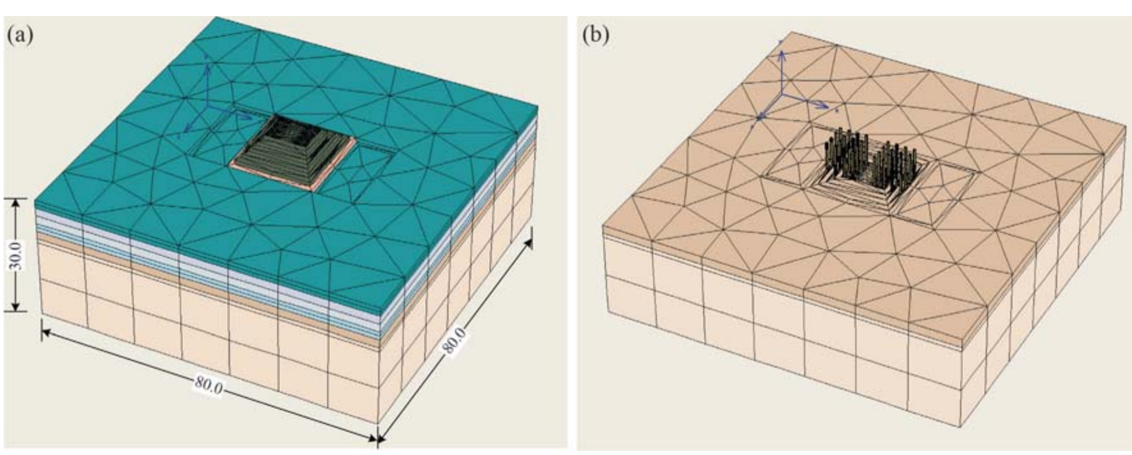

Figure 8 - Embankment simulation model used in 3D FEM simulation.

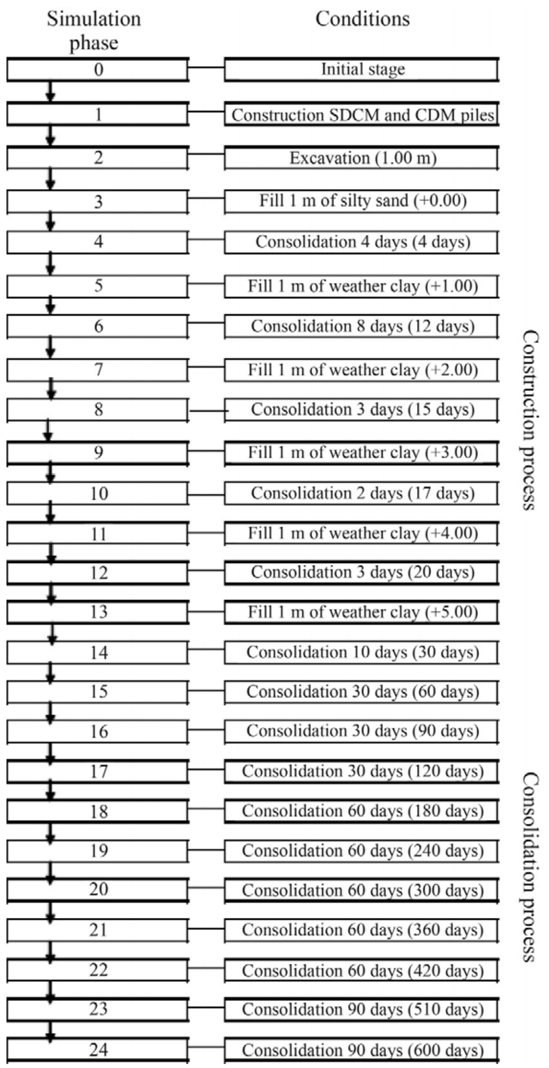

Figure 9 - Finite element simulation for full scale embankment load test.

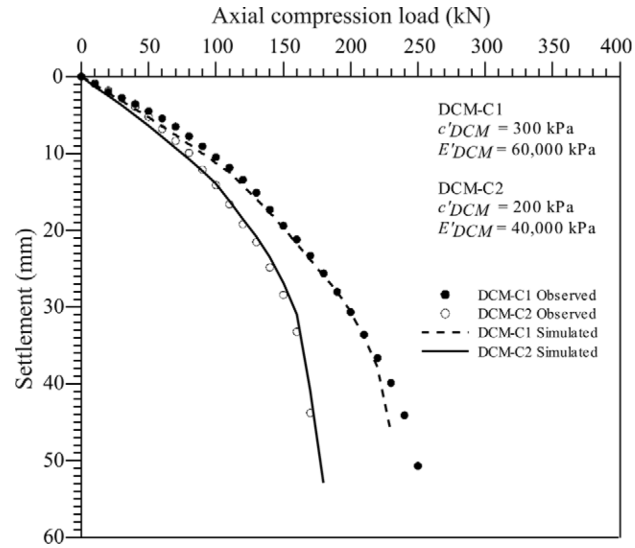

Figure 10 - Comparisons between observed and simulated axial compression load – settlement curves for DCM-C1 and DCM-C2.

sion in the DCM pile, C_{DCM}, obtained from the 3D finite element simulations were 300 kPa and 200 kPa, respectively, as illustrated in Fig. 10. However, the cement-clay modulus, E_{DCM}, were obtained as 60,000 kPa and 40,000 kPa for DCM C-1 and DCM C-2, respectively. Furthermore, for the SDCM pile, the corresponding value for C_{DCM} and E_{DCM} were 200 kPa and 30,000 kPa, respectively, as illustrated in Fig. 11. The slightly different results reflect the construction quality control in the field tests.

Figure 12 shows the summary of the ultimate bearing capacity of SDCM pile which proportionally increased linearly with the increased lengths of concrete core pile while the sectional areas of the concrete core pile only slightly increased the bearing capacity. Consequently, increasing the length ratio, L_{core}/L_{DCM}, has dominant effect than increasing the se

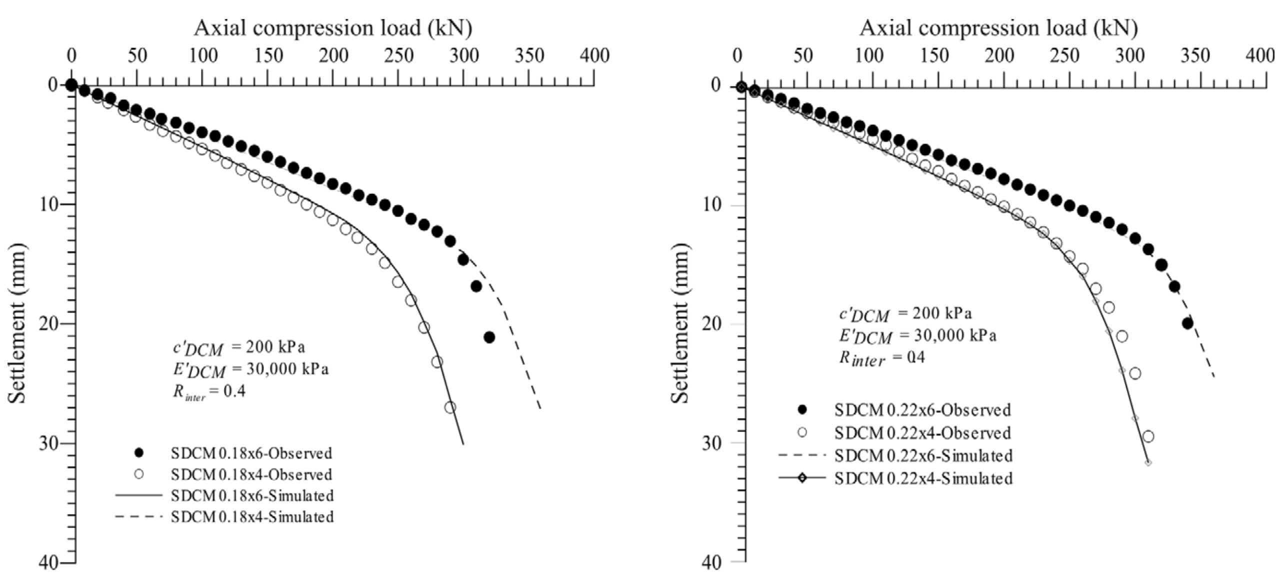

Figure 11 - Comparisons between observed and simulated axial compression load – settlement curves for SDCM.

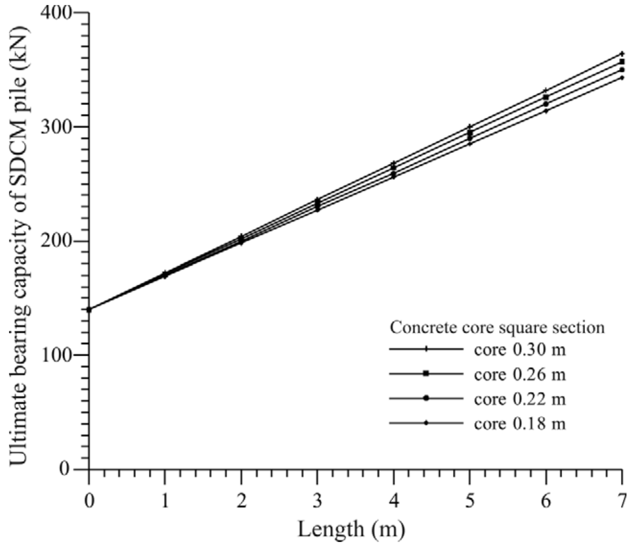

Figure 12 - Effect of lengths and sectional areas of concrete core piles on ultimate bearing capacity.

The mode of failure consisted of three categories, namely: concrete core pile failure, DCM pile failure, and soil failure. The SDCM pile failure occurred in the unreinforced part (DCM pile failure) because the DCM pile was not strong enough to carry and transfer the load to the tip of DCM pile as demonstrated in Fig. 13.

6.2. Lateral load simulation

The appropriate values for mixture of cement-clay cohesion in the DCM pile, C_{DCM}, and mixture of cement-clay modulus, E_{DCM}, obtained from the 3D finite element simulation were similar to that in the axial compression pile. In addition, the tensile strength of DCM pile, T_{DCM}, and tensile strength of concrete core, Tcore, were evaluated in this study. The T_{DCM} obtained from the simulation of DCM pile were 50 kPa and 25 kPa for DCM L-1 and DCM L-2, respectively, and the corresponding values for T_{core} and T_{DCM} obtained from the simulation were 5000 kPa and 50 kPa, respectively (Figs. 14 and 15).

The ultimate lateral load of SDCM pile increased with increasing sectional area because it increased the stiffness of the SDCM pile but the length of concrete core pile did not increase the ultimate lateral load capacity when using concrete core pile lengths longer than 3.5 m. (Fig. 16).

6.3. Embankment load simulation

The surface settlements were measured at the top of DCM, SDCM piles and the unimproved ground in the middle of the embankment (untreated clay). The observed settlements are plotted in Fig. 17 together with the simulated values. Both the magnitude and rate of settlements from simulations agreed well with the observed data from field test as illustrated in Fig. 17. Consequently, the parameters involved were derived and verified. The parametric study was conducted by varying the sectional areas of the concrete core pile of 0.22 x 0.22 m and 0.30 x 0.30 m as well as varying the lengths of concrete core piles of 4, 5, 6 and 7 m to study their effects on the embankment settlements. The effects of lengths and sectional areas of the concrete core

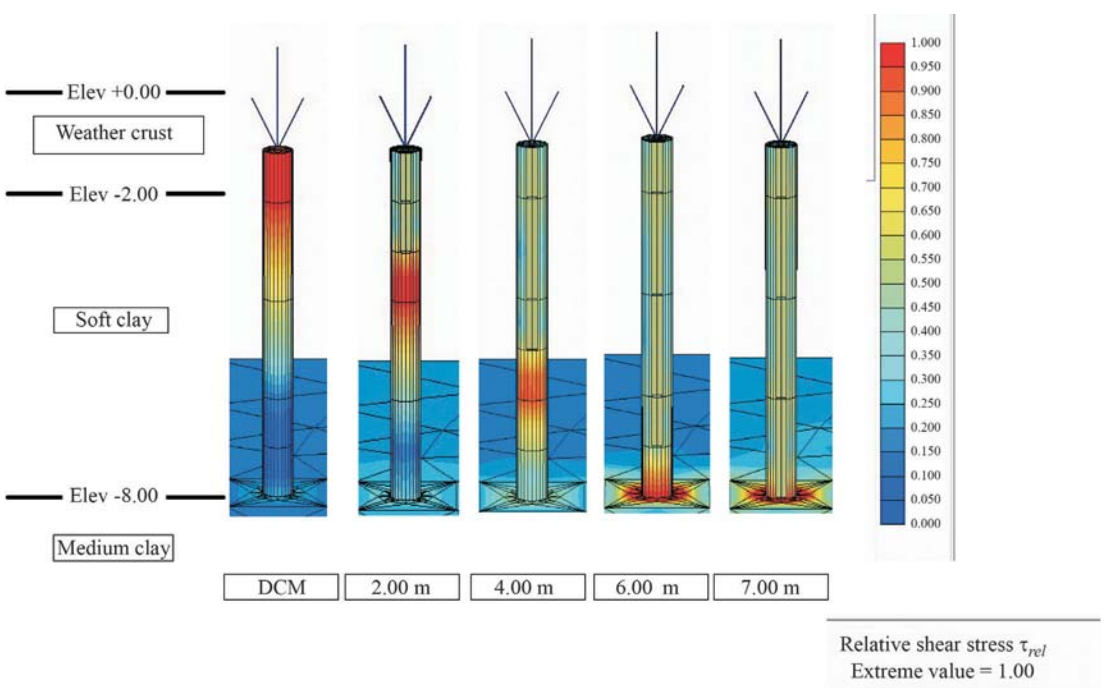

Figure 13 - Relative shear stresses of 0.22 x 0.22 m core piles at failure load from simulations.

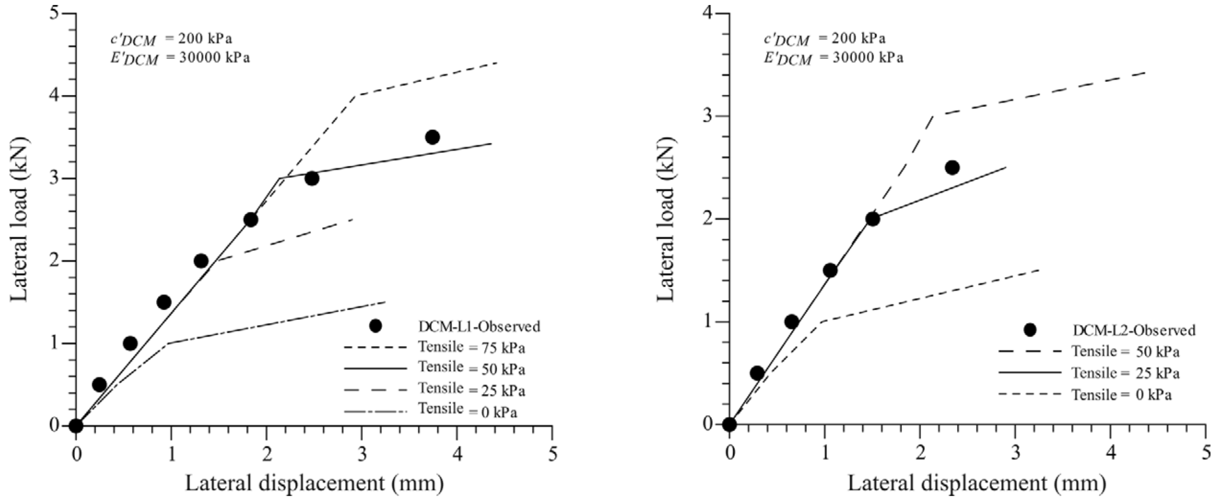

Figure 14 - Comparisons between observed and simulated lateral load – settlement curves for DCM-L1 and DCM-L2.

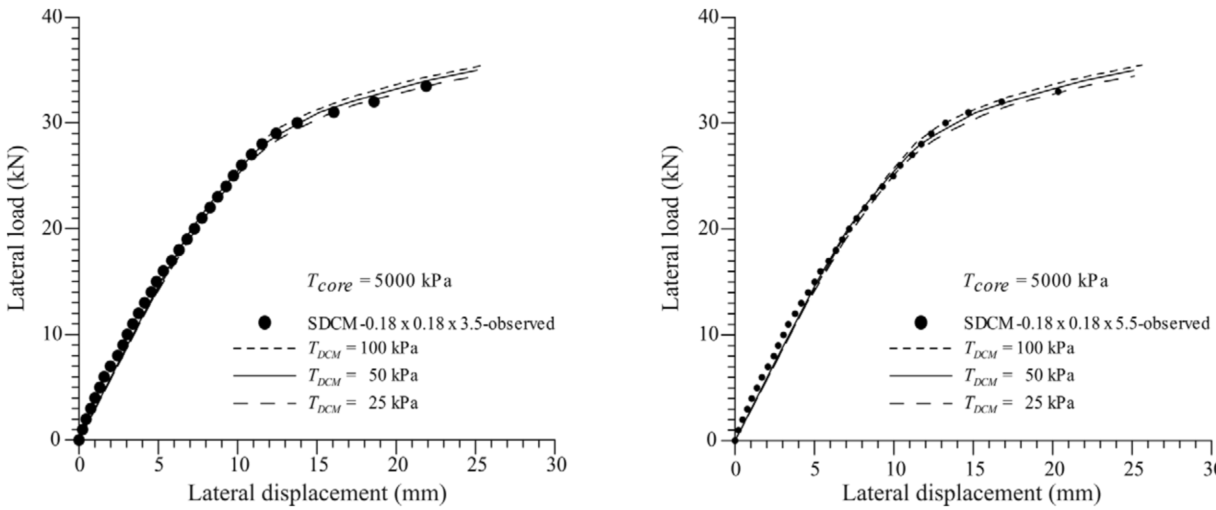

Figure 15 - Comparisons between observed and simulated lateral piles load – settlement curves for SDCM.

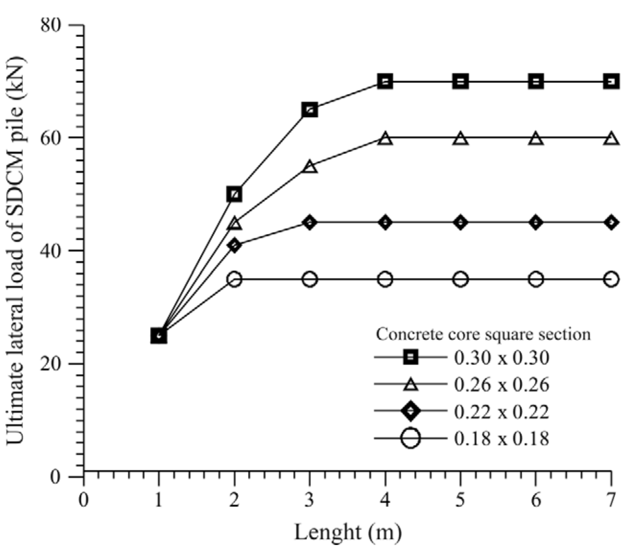

Figure 16 - Effect of lengths and sectional areas of concrete core piles on the ultimate lateral load of SDCM pile.

piles of SDCM piles on the ultimate settlement of embankment simulation are illustrated in Fig. 18. It can be summarized that the ultimate settlement at 600 days after consolidation proportionally decreased with increasing lengths of concrete core piles from 4 to 6 m and only slightly decreased from lengths of 6 to 7 m. Moreover, the ultimate settlement only slightly decreased when increasing the sectional areas of the concrete core piles from 0.22 to 0.30 m.

Figure 19 shows the summary of the effect of core pile length on the settlement at 600 days after consolidation in surrounding clay of SDCM pile. The settlement of surrounding clay of SDCM at surface and 4 m depth decreased with increasing the lengths of concrete core pile and only slightly decreased with increasing the sectional areas. Therefore, it can be concluded that the ultimate settlements proportionally reduced with increasing lengths of concrete core pile. In addition, both the sectional area and length of concrete core pile have no effect in the subsurface settlement at 7 m depth.

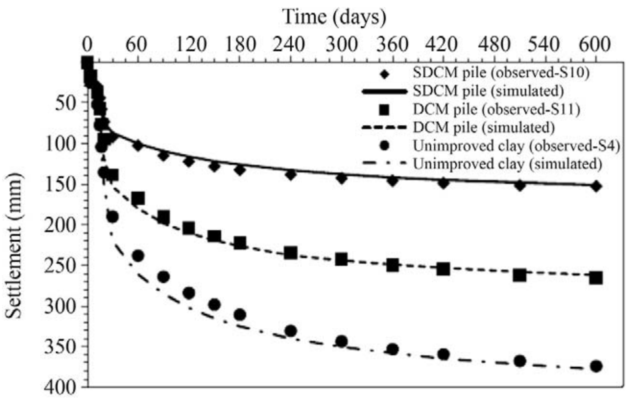

Figure 17 - Comparison of observed and simulated surface settlements.

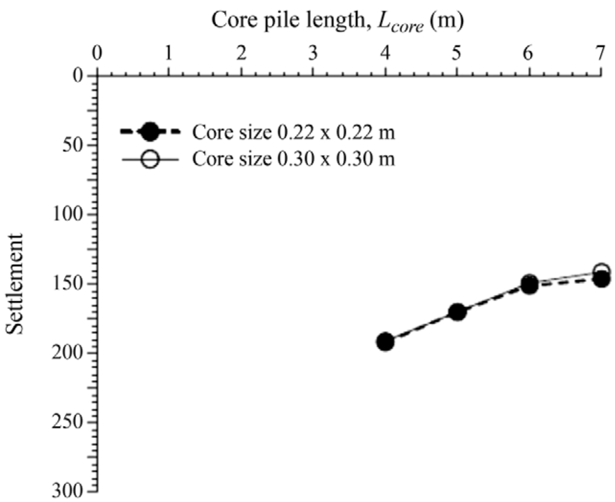

Figure 18 - Effect of lengths and sectional areas of concrete core pile on ultimate settlements of SDCM pile.

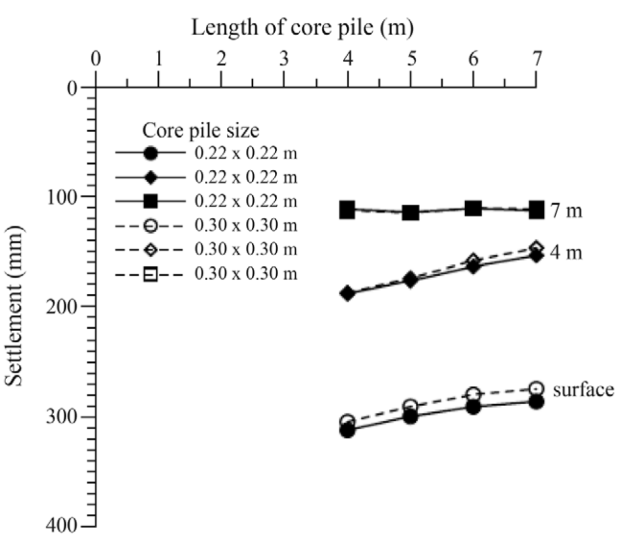

Figure 19 - Effects of core pile lengths on ultimate surface and subsurface settlements in surrounding clay of SDCM pile.

Differential settlements occur in the subsurface at various depths because the stresses proportionally decreased from the surface to the depths 4 and 7 m, respectively. Moreover, the stresses in the surrounding clay of SDCM and DCM piles as well as the unimproved zone are plotted together in Fig. 20. The stresses of surrounding clay of SDCM is the lowest meaning that the lowest settlements at the surface and 4 m depth. For the 7 m depth, the stresses are only slightly different so the settlements were similar.

The effect of length of concrete core pile on the lateral movements are also studied through the simulations by varying the lengths of the concrete core pile from 4 to 7 m as well as their sectional areas consisting of 0.22 x 0.22 m and 0.30 x 0.30 m. The simulated and observed results of the lateral movements for both DCM and SDCM piles at different periods after construction are illustrated in Fig. 21. The observed lateral movements were obtained from inclinometers as indicated in Fig. 5a,b. The measured and simulated lateral movement data agreed well. The effects of concrete core pile lengths longer than 4 m on lateral movements' profiles of SDCM piles at 570 days after construction are illustrated in Fig. 22. The lateral movement reduced with increasing lengths of concrete core piles longer than 4 m. From subsequent simulations as shown in Fig. 23, increasing the lengths and, to a lesser degree, the sectional areas of concrete core piles, reduced the lateral movements of the SDCM piles for concrete core piles longer than 4 m. The lateral movement significantly reduced with increasing lengths as well as with increasing the sectional areas of concrete core piles. It can be summarized that increasing both the lengths and sectional areas of core piles reduced the lateral movement.

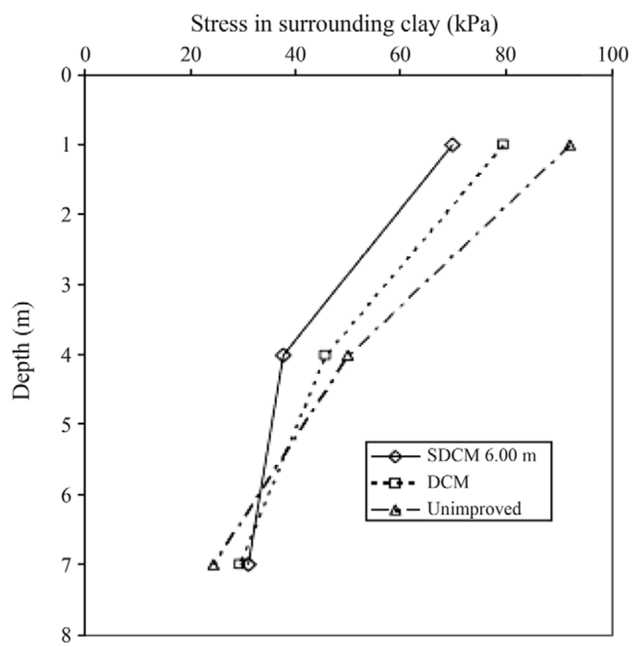

Figure 20 - Stresses in surrounding clay of unimproved zone, SDCM and DCM piles piles at depth 1, 4 and 7 m.

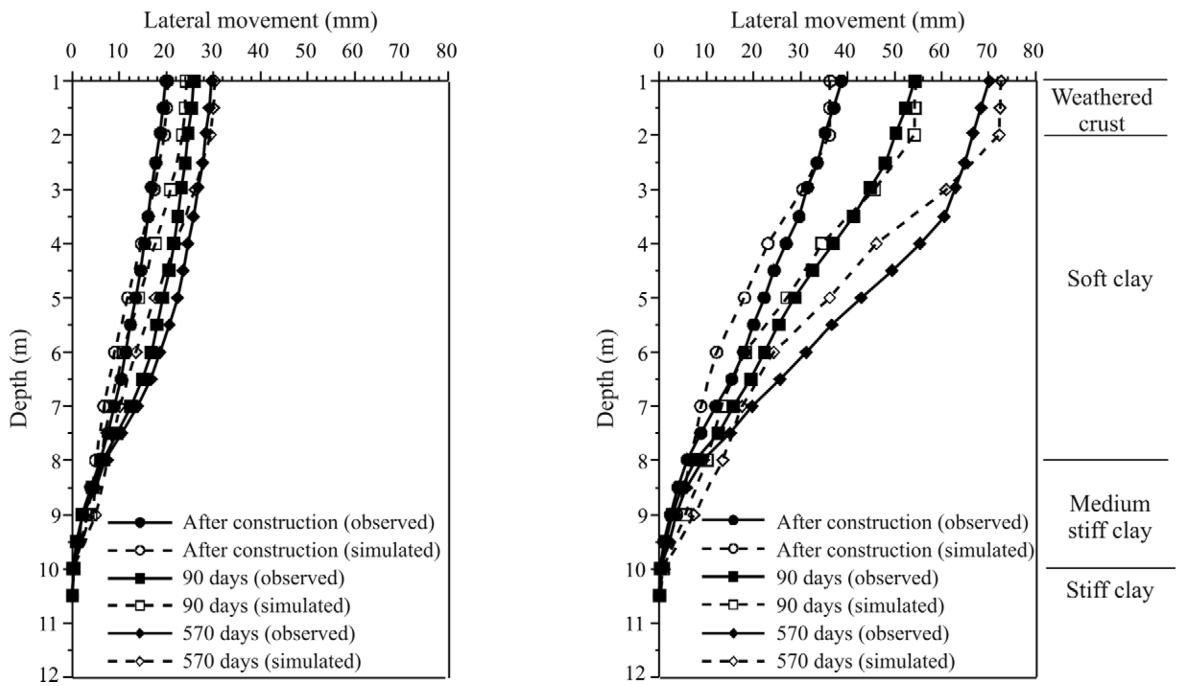

Figure 21 - The simulated and observed lateral movements of SDCM and DCM piles at different periods after construction.

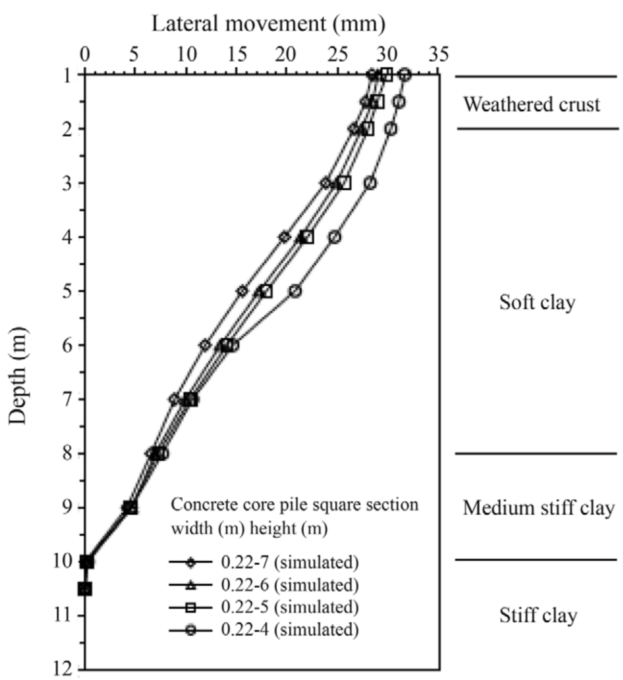

Figure 22 - Effects of concrete core pile lengths on lateral movement profiles of SDCM pile with 0.22 x 0.22 m core pile from simulations.

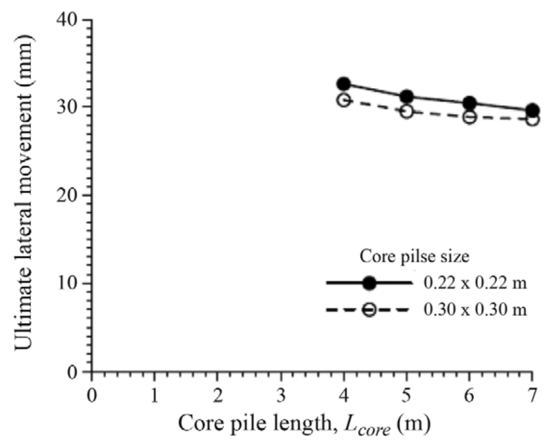

Figure 23 - Effects of sectional areas and lengths of concrete core piles on the maximum lateral movement of SDCM pile.

6.4. Axial compression pile simulation

For the SDCM pile, the corresponding values for cement-clay cohesion in the DCM pile, C_{DCM}, and corresponding modulus, E_{DCM}, were found to be 200 kPa and 30,000 kPa, respectively. The relative shear stresses for both SDCM and DCM piles under embankment load are illustrated in Figs. 24 and 25 corresponding to concrete core pile length of 6.0 m and DCM pile length of 7.0 m. It is indicated that larger relative stresses occurred in the DCM piles compared to the SDCM piles resulting in more compressions in the former than the latter which agree with the vertical deformations in Fig. 17 and lateral deformations plotted in Fig. 21.

7. Conclusions

The full scale embankment loading test supported by SDCM and DCM piles was constructed, monitored and, consequently, simulated by using Plaxis Foundation 3D software in order to study and verify the design parameters.

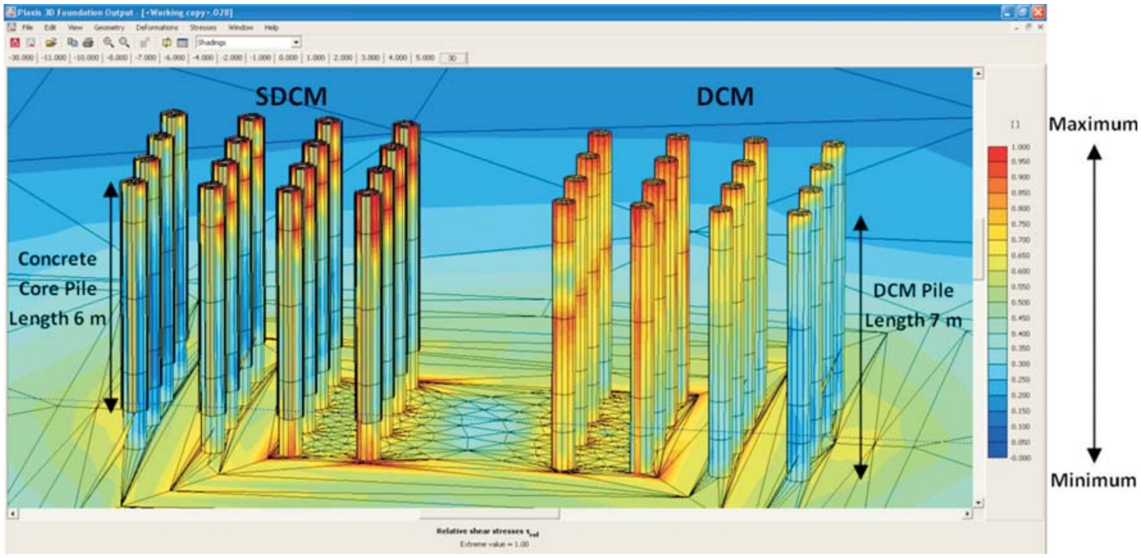

Figure 24 - Relative shear stresses of DCM piles with 7.0 m length and SDCM piles with 0.22 x 0.22 m by 6.0 m concrete core piles under embankment loading.

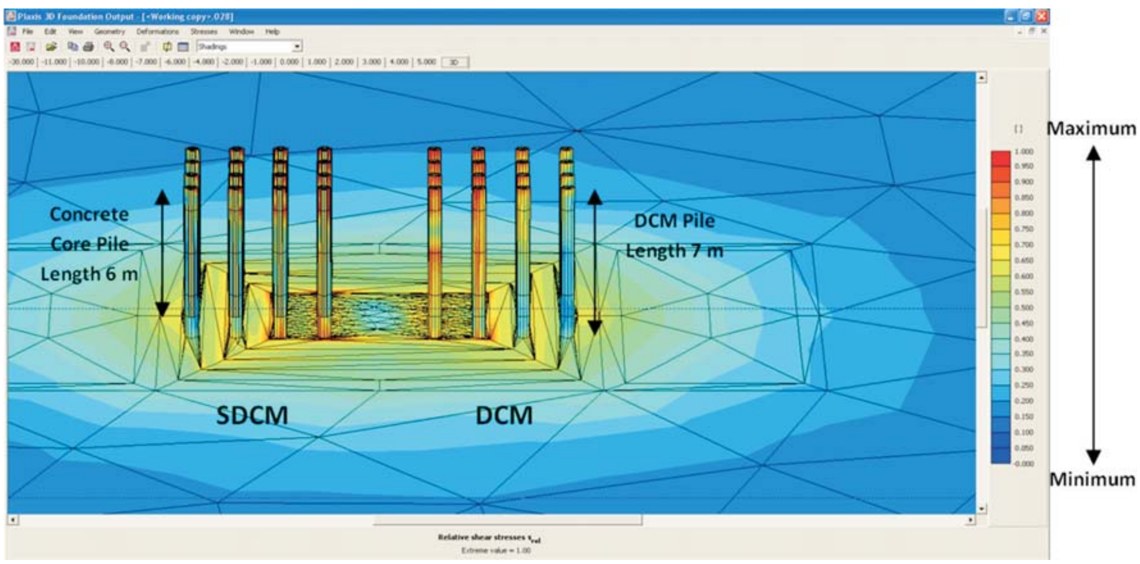

Figure 25 - Cross section view of relative stresses of DCM and SDCM pile under embankment loading.

The parameters were also based on an earlier full scale load tests to failures and subsequent simulations. The appropriate parameter for cement-clay cohesion, C_{DCM}, and cement-clay modulus, E_{DCM}, obtained from the 3D finite element simulations were 200 kPa and 30,000 kPa, respectively. The result indicated that the longer concrete core pile can reduce the vertical displacements of SDCM pile as well as the subsurface portions of the surrounding soil. The settlements reduced with increasing lengths of concrete core piles from 4 to 6 m but slightly reduced from 6 to 7 m core pile length. Moreover, the length of concrete core pile affected both the surface and subsurface settlements at 4 m but did not affect the subsurface settlement at 7 m. In case of lateral deformation, the length and sectional areas of concrete core pile reduced the lateral movement of the embankment. The longer the lengths, the lower the lateral movements. Furthermore, the bigger sectional areas also reduced the lateral movements although with smaller effects. It was also found in the previous and current studies that, the concrete core piles need to be longer than 4 m in order to effectively reduce the lateral movements of the embankment.

References

Bhandari, A. (2006) Laboratory Investigation of Stiffened Deep Cement Mixed (SDCM) Pile. M.Sc. Eng. Thesis

No. GT-78-6, Asian Institute of Technology, Bangkok, 97 pp.

Bergado, D.T.; Ahmed, S.; Sampaco, C.L. & Balasubramaniam, A.S. (1990) Settlement of Bangna-Bangpakong highway on soft Bangkok clay. ASCE Journal of Geotechnical Engineering, v. 116:1, p. 136-154.

Brinkgreve, R.B. & Broere, W. (2006) Manual PLAXIS 3D Foundation ver. 1.6. A.A. Balkema, Rotterdam, 177 pp.

Butler, H.D. & Hoy, H.E. (1997) The Texas Quick Load Method for Foundation Load Testing – User's Manual. Federal Highway Administration, Report No. FHWA-IP-77-8, Texas, 54 pp.

Dong, P.; Qin, R. & Chen, Z. (2004) Bearing capacity and settlement of concrete-cored DCM pile in soft ground. Geotechnical and Geological Engineering, v. 22:1 p. 105-119.

Jamsawang, P. (2008) Full Scale Tests on Stiffened Deep Cement Mixing (SDCM) Pile Including 3d Finite Element Simulation. D. Eng. Diss. No. GE-08-01, Asian Institute of Technology, 235 pp.

Jamsawang, P.; Bergado, D.T.; Bandari, A. & Voottipruex, P. (2008) Investigation and simulation of behavior of stiffened deep cement mixing (SDCM) piles. International Journal of Geotechnical Engineering, v. 2:3, p. 229-246.

Jamsawang, P.; Bergado, D.T.; Bandari, A. & Voottipruex, P. (2009a) Behavior of stiffened deep cement mixing pile in laboratory. Lowland International Journal, v. 11:1, p. 20-28.

Jamsawang, P.; Bergado, D.T. & Voottipruex, P. (2009b) Laboratory and field behavior of stiffened deep cement mixing (SDCM) pile. Ground Improvement Journal, v. 164:G11, p. 33-49.

Petchgate, K.; Jongpradist, P. & Panmanajareonphol, S. (2003a) Field pile load test of soil-cement column in soft clay. In: Proceedings of the International Symposium 2003 on Soil/Ground Improvement and Geosynthetics in Waste Containment and Erosion Control Applications, Asian Institute of Technology, Thailand, pp. 175-184.

Shinwuttiwong, W. (2007) Full Scale Behavior of SDCM Piles under Axial and Lateral Loading with Simulations. M.Sc. Eng. Thesis No GE-07-04, Asian Institute of Technology, Bangkok, 139 pp.

Suksawat, T. (2009) Numerical simulation of SDCM and DCM piles under axial and lateral loads and under embankment load: A parametric study. M.Sc. Eng. Thesis No. GE-08-09, Asian Institute of Technology, Bangkok, 143 pp.

Tand, K.E. & Vipulanandan, C. (2008) Comparison of computed vs. measured lateral load/deflection response of ACIP piles. Plaxis Bulletin, v. 23, p. 10-13.

Wehnert, M. & Vermeer, P.A. (2004) Numerical analysis of load tests on bored piles. NUMOT 9th, Ottawa, pp. 505-511.

Wu, M.; Zhao, X. & Dou, Y.M. (2005) Application of stiffened deep cement mixed column in ground improvement. In: Proceedings International Conference on Deep Mixing Best Practices and Recent Advances, Stockholm, pp. 463-468.

Zheng, G. & Gu, X.L. (2005) Development and practice of composite DMM column in China. In: Proceedings 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka, v. 3, pp. 1295-1300.