BEHAVIOR AND SIMULATION OF DEEP CEMENT MIXING (DCM) AND STIFFENED DEEP CEMENT MIXING (SDCM) PILES UNDER FULL SCALE LOADING

P. VOOTTIPRUEX, D. T. BERGADO, T. SUKSAWAT, P. JAMSAWANG and W. CHEANG

ABSTRACT

A new kind of Deep Cement Mixing (DCM) pile called Stiffened Deep Mixing Pile (SDCM) is introduced to mitigate the low flexural strength and unexpected failures of DCM piles. A jet grouting method with a jet pressure of 22 MPa, was utilized in the installation of DCM piles. The SDCM pile consists of a DCM pile with a precast reinforced concrete core pile inserted at its center. Pile and embankment load tests were conducted, and then the results of the field load tests were simulated by a 3D finite element method (FEM) to back-analyze and confirm the related design parameters. These parameters were then used further in numerical experiments. The field test results showed that the settlements and lateral movements of the SDCM pile using a prestressed concrete core pile with area ratio ($A_{core}/A_{DCM}$) of 0.17 and a length ratio of 0.85 was less than those of the DCM pile by 40\% and 60\%, respectively. Moreover, the SDCM pile foundation increased the bearing capacity by as much as 2.2 times. The average lateral pile capacity of the SDCM piles was 15 times higher than the DCM piles. A strength reduction factor of 0.40 was obtained at the concrete core and the DCM interface from the full scale pullout test. The behavior of both the DCM and SDCM piles was confirmed from the subsequent 3D FEM simulations. From the 3D FEM simulations, the length of the concrete core pile had more influence on the settlements of the SDCM pile than its cross-sectional area. However, both the length and cross-sectional area of concrete core pile affected the lateral resistance of the SDCM pile.

Key words: consolidation settlement, deep cement mixing, pile load tests, soft clay, stiffened deep cement mixing, test embankment, unconfined compression tests (IGC: E13/K14)

INTRODUCTION

Deep cement mixing (DCM) pile is widely used to support embankments and lightly-loaded structures on soft ground. The behavior of the DCM pile under embankment loading on soft Bangkok clay has been studied by Chen (1990), Honjo et al. (1991), Bergado et al. (1999), Lin and Wong (1999) and Lai et al. (2006). DCM piles have been shown to have variable strength and stiffness due to poor workmanship (Petchgate et al., 2003a, b; 2004) leading to low bearing capacity and large settlements for piles failure instead of soil failure (Fig. 1(a)). Figure 1(b) shows the loading test results of DCM piles in soft Bangkok clay by Petchgate (2003a, b). The results of the field tests show almost half of the DCM piles failed by pile failure instead of soil failure. In the case of pile failure, the bearing capacity of the DCM pile tends to be lower than the design load of 10 tons (below the black line in Fig. 1(b)) implying low quality DCM material. Another problem is that DCM piles are sometimes subjected to both vertical and horizontal forces induced by the embankment loads even though they are not suitable for medium to high design loads (Dong et al., 2004). If DCM piles are to be subjected to a heavy load, the designer needs to ensure a higher ground improvement ratio, which can be achieved by a larger amount of cement and higher strength cement. Therefore, a new technology called the Stiffened Deep Cement Mixing (SDCM) pile employs a precast concrete core pile inserted at the center of DCM pile. This concrete core pile takes most of the load and transmits it to the surrounding soil-cement through the interfaces between the concrete core pile and the DCM pile. The SDCM pile is more suitable than the DCM pile because the SDCM pile has higher strength and stiffness and can sustain both higher bending moments and higher lateral loads. A series of pile load tests were conducted to investigate the behavior of SDCM piles in China by Dong et al. (2004), Wu et al. (2005), and Zheng.
et al. (2005). Most of the tests were only concerned with the bearing capacities of the SDCM piles. Recently, Jamsawang et al. (2008) measured and simulated the settlement behavior of composite foundations consisting of a SDCM pile with a concrete core pile in laboratory model tests.

In this paper, comprehensive research results on the behavior of Stiffened Deep Cement Mixing (SDCM) are presented and compared to the behavior of the traditional Deep Cement Mixing (DCM). Included are the test results and analyses of field full scale load tests on DCM and SDCM piles as well as their behavior under a 5 m high full scale embankment loading. The results of the 3D numerical simulations performed in order to back-analyze the design parameters are also reported, and these parameters were utilized further in numerical experiments which considered sensitivity and also in calibrated FEM analyses.

Stiffened Deep Cement Mixed (SDCM) Piles

Stiffened deep cement mixing (SDCM) pile is a composite structure of concrete core pile and deep cement mixing pile. The prestressed concrete core pile is inserted into the center of the DCM pile immediately 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, in effect increasing its stiffness and ability to resist the compressive stresses along the pile shaft. It should be noted that this novel method of improving the strength of DCM pile has been referred to by different terminology over the years, including the concrete cored DCM pile (Dong et al., 2004), the composite DMM column (Zheng et al., 2005) and the stiffened deep cement mixed (SDCM) column method (Wu et al., 2005).

Each SDCM pile was constructed by inserting a prestressed concrete core pile in the middle of a DCM pile with a 0.6 m diameter and length of 7.0 m (Fig. 2(a)). The jet grouting technique, using a jet pressure of 22 MPa with a water-cement ratio of 1.5, was utilized in the installation of the DCM piles. The concrete core pile was inserted into the SDCM pile immediately after the deep mixing process had completed. During the curing period, the concrete core pile was anchored at the ground surface to prevent it from sinking. The deep mixing piles were allowed to cure for about 80 days. The prestressed concrete pile was selected as the stiff core because of its high strength and stiffness and also because it is cheaper than steel pile. The concrete core pile (Fig. 2(b)) consisted of \(0.18 \times 0.18\) m and \(0.22 \times 0.22\) m square cross sections and 4.0 and 6.0 m in lengths corresponding area ratio, defined as the sectional area of core pile over a sectional area of the DCM pile (\(A_{core}/A_{DCM}\)), and length ratio, defined as the length of core pile over the length of the DCM pile (\(L_{core}/L_{DCM}\)), of 0.11 and 0.17 as well as 0.57 and 0.85, respectively (Table 1).

The compressive strength of the concrete core pile was found to be 35 MPa. For the numerical simulation, the length of the concrete pile was varied from 1.00 m to 7.00 m with 1.0 m increments to evaluate the effect of the length of the concrete core pile on the capacity of the SDCM pile. The Mohr-Coulomb model was recommended to simulate the concrete core pile instead of the linear
elastic model because its stiffness can be overestimated if the tensile strain is large enough to crack the concrete (Tand and Vipulandan, 2008).

**Project Site and Subsoil Profile**

Full scale axial and lateral pile load tests were performed by Shinwuttiwong (2007) and Jamsawang (2009) 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 weathered crust, which is underlain by 6.0 m of a 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 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., 2002b). The other parameters are shown in Table 2.

**FULL SCALE PILE LOAD TESTS**

**Testing Program**

A series of full scale load tests on SDCM and DCM piles under axial compression load and lateral load were performed to determine their ultimate bearing capacities and lateral resistances. In addition, two pullout interface tests between the concrete core and deep cement mixing were also conducted to determine the interface resistance between the concrete core and the deep cement mixing pile. The full scale test was monitored in order to study its consolidation and deformation behavior and the performances of the SDCM and DCM pile foundations were compared. The SDCM and DCM piles were constructed beneath the test embankment with 2.0 m spacing (Fig. 4).

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**Table 1. The effective value of the length ratio and area ratio**

<table>
<thead>
<tr>
<th>$L_{DCM}$ (m)</th>
<th>$D_{DCM}$ (m)</th>
<th>$L_{core}$ (m)</th>
<th>Core size ($m \times m$)</th>
<th>$L_{core}/L_{DCM}$</th>
<th>$A_{core}/A_{DCM}$</th>
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</thead>
<tbody>
<tr>
<td>7.0</td>
<td>0.60</td>
<td>6.0</td>
<td>0.22 x 0.22</td>
<td>0.85</td>
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<tr>
<td>7.0</td>
<td>0.60</td>
<td>6.0</td>
<td>0.18 x 0.18</td>
<td>0.85</td>
<td>0.11</td>
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<tr>
<td>7.0</td>
<td>0.60</td>
<td>4.0</td>
<td>0.22 x 0.22</td>
<td>0.57</td>
<td>0.17</td>
</tr>
<tr>
<td>7.0</td>
<td>0.60</td>
<td>4.0</td>
<td>0.18 x 0.18</td>
<td>0.57</td>
<td>0.11</td>
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</tbody>
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**Table 2. Soil models and parameters used in 3D FEM simulation**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Model</th>
<th>Depth (m)</th>
<th>$\gamma$ (kN/m^3)</th>
<th>Material behavior</th>
<th>$E_{sat}$ (kPa)</th>
<th>$\phi'$</th>
<th>$\lambda$</th>
<th>$k_s$ (kPa)</th>
<th>$c'$ (kPa)</th>
<th>$\theta'$ (deg)</th>
<th>$k_f$ (m/day)</th>
<th>OCR</th>
<th>Tensile Strength (kPa)</th>
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<tbody>
<tr>
<td>Subsoil</td>
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<tr>
<td>Weathered crust</td>
<td>MCM</td>
<td>0–2.0</td>
<td>17</td>
<td>Undrained</td>
<td>2500</td>
<td>0.25</td>
<td>0.01</td>
<td>10</td>
<td>23</td>
<td>$1 \times 10^{-3}$</td>
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<td></td>
<td></td>
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<tr>
<td>Soft clay</td>
<td>SSM</td>
<td>2.0–8.0</td>
<td>15</td>
<td>Undrained</td>
<td>5000</td>
<td>0.25</td>
<td>0.02</td>
<td>10</td>
<td>25</td>
<td>4 $\times 10^{-4}$</td>
<td>1.5</td>
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<tr>
<td>Medium stiff clay</td>
<td>MCM</td>
<td>8.0–10.0</td>
<td>18</td>
<td>Undrained</td>
<td>9000</td>
<td>0.25</td>
<td>0.03</td>
<td>30</td>
<td>26</td>
<td>4 $\times 10^{-4}$</td>
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<tr>
<td>Stiff clay</td>
<td>MCM</td>
<td>10.0–30.0</td>
<td>19</td>
<td>Undrained</td>
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<tr>
<td>Concrete core pile</td>
<td>MCM</td>
<td>24</td>
<td>24</td>
<td>Drained</td>
<td>2.8 $\times 10^7$</td>
<td>0.15</td>
<td>8000</td>
<td>40</td>
<td>5000</td>
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<tr>
<td>DCM pile (with interface elements)</td>
<td>MCM</td>
<td>15</td>
<td>Undrained</td>
<td>30000-60000</td>
<td>0.33</td>
<td>100-300</td>
<td>30</td>
<td>0.012</td>
<td>0-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel plate</td>
<td>LEM</td>
<td></td>
<td>Non-porous</td>
<td></td>
<td>2.1 $\times 10^9$</td>
<td>0.15</td>
<td></td>
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SSM: soft soil model; MCM: Mohr-Coulomb model; LEM: linear elastic model
Unconfined Compression Tests on Deep Cement Mixing Core Samples

To obtain the engineering properties of the DCM pile in the test site, three DCM piles were constructed (Fig. 4) so that core samples could be extracted for unconfined compression tests in the laboratory in order to determine the unconfined compressive strength, $q_u$, and the modulus of elasticity corresponding to 50% unconfined compressive strength, $E_{50}$. Unconfined compressive tests were performed on samples 50 mm in diameter and with a height of 100 mm. The values were scattered over the entire depth without any clear trend of the influence of the depth on the values of unconfined compressive strength and the modulus of elasticity (Fig. 5(a)). The values of unconfined compressive strength ranged from 500 kPa to 1,500 kPa with an average value of 900 kPa while the modulus of elasticity ranged from 50,000 kPa to 150,000 kPa with an average value of 90,000 kPa, indicating that $E_{50} = 101q_u$ as shown in Fig. 5(b). It can be seen that the correlation ratio of $E_{50}/q_u$ obtained from field coring samples ranged from 60 to 150.

Axial Load Tests

Two axial load tests on SDCM piles (SDCM-C1 and SDCM-C2) and two axial load tests on DCM piles (DCM-C1 and DCM-C2) were conducted in accordance with ASTM D-1143, *Quick Load Test Method for Individual Piles under Static Axial Compression Load*. The load was applied in increments of 10 kN. Each load increment was maintained for 5 min. The load was applied until continuous settlement occurred with either a slight increase or no increase in the axial load. Figure 6 shows the axial compression load versus the settlement relationships for all four test piles. The ultimate bearing capacities of all test piles were determined by the slope tangent method at the point of intersection of the initial and final tangents in the load settlement curve, as established by Butler and Hoy (1977). The ultimate bearing capacities of the DCM piles, DCM-C1 and DCM-C2, were 220 kN and 140 kN, respectively. The large difference in the ultimate bearing capacities of DCM-C1 and DCM-C2, as much as 80 kN, confirmed the low quality that commonly occurs in DCM piles which results in its low bearing capacity (Petchgate et al., 2003a). The ultimate bearing capacities of the SDCM piles, SDCM-C1 and SDCM-C2, were 320 kN and 310 kN, respectively. No significant difference in the ultimate bearing capacities of these SDCM piles and their
load settlement curves was observed. Their more consistent ultimate bearing capacities imply that the concrete core improved the quality and increased the bearing capacity as well as the stiffness of the SDCM pile. The average ultimate bearing capacity of the SDCM pile with a 0.22 m square and 6 m long concrete core pile was 315 kN, which is 1.4 and 2.2 times, respectively, higher than those of DCM-C1 and DCM-C2 piles.

Lateral Load Tests

Two lateral load tests on SDCM piles (SDCM-L1 and SDCM-L2) and two lateral load tests on DCM piles (DCM-L1 and DCM-L2) were conducted in accordance with ASTM D-3966, Standard Lateral Loading Procedure. The load was applied in increments of 1 kN. Each load increment was maintained for 10 min. The load was applied until continuous lateral displacements occurred with either a slight increase or no increase in load. Figure 7 shows the lateral load versus the lateral displacement relationships for all four test piles. The ultimate lateral loads of the DCM piles, DCM-L1 and DCM-L2, were 3.5 kN and 2.5 kN, respectively, with an average ultimate lateral load of 3.0 kN, which is very low due to the low flexural strength (Terashi and Tanaka, 1981; Petchgate et al., 2004). The ultimate lateral loads for the SDCM piles, SDCM-L1 and SDCM-L2, were 46 kN and 45 kN, respectively, with an average ultimate lateral load of 45.5 kN, which is 15 times greater than that for the DCM pile. Moreover, much less lateral displacement was observed for the SDCM pile than for the DCM pile at the same load, implying that the SDCM pile has much higher flexural stiffness than the DCM pile. Based on the compression and lateral load tests, SDCM piles, with their higher stiffness and ultimate bearing capacity, and especially higher flexural stiffness and strength, are more suitable than DCM piles for embankment foundations subjected to vertical and horizontal loads.

Pullout Load Tests

Finally, two pullout load tests (Pullout-T1 and Pullout-T2) were performed in accordance with ASTM D-3689, Quick Load Test Method for Individual Piles under Static Axial Tensile Load. The length of the concrete core pile embedded in SDCM pile was 1.0 m for all tests. The load was applied in increments of 5 kN. Each load increment was maintained for 5 min. The load was applied until continuous vertical displacements occurred with a slight increase or no increase in load. Figure 8 shows the tension load versus vertical displacement relationships. The maximum tension loads were 165 kN and 155 kN for the test piles, Pullout-T1 and Pullout-T2, respectively, with average maximum tensile load of 160 kN. The interface shear strength ($\tau_{\text{interface}}$) was calculated by dividing the maximum tensile load by the surface area of the concrete core embedded in the DCM pile. Consequently, the strength reduction factor for interfaces ($R_{\text{inter}}$) defined by Brinkgreve and Broere (2006) is:

$$R_{\text{inter}} = \frac{\tau_{\text{interface}}}{c_{\text{soil}}} = \frac{182}{450} = 0.40$$

This value is within the range of pullout interface test results on concrete core and cement-admixed clay performed in the laboratory by Jamsawang et al. (2008), ranging from 0.38 to 0.46.
Prior to embankment construction, the foundation subsoil was improved with SDCM and DCM piles. The DCM piles were installed in situ by a jet mixing method employing a jet pressure of 22 MPa. Both SDCM and DCM piles were installed at 2.0 m spacing as shown in Figs. 9(a) and (b). The water-cement ratio (w/c) of the cement slurry and the cement content employed for the construction of deep mixing were 1.5 and 150 kg/m³ of soil, respectively. Each deep mixing pile had a diameter of 0.6 m and a length of 7.0 m and penetrated down to the bottom of the soft clay layer, as shown in the section view of the embankment (Fig. 9(b)).

Field Instrumentations
To observe the behavior of SDCM and DCM piles under embankment loading as well as the behavior of the test embankment, various instruments were installed at the site. Figures 9(a) and (b) show the instrumentation in plan and cross-sectional views, respectively. Five surface settlement plates were installed to a depth of 1.0 m from the original ground. The surface settlement plates were installed on both the top of the SDCM pile (S10) and DCM pile (S11), on the surrounding clay of SDCM pile (S1) and DCM pile (S7) and on the unimproved clay (S4). The installations were carried out after an excavation of 1.0 m depth, the base level of the test embankment. Six subsurface settlement gauges were also installed at 4.0 m and 7.0 m depths from the original ground. Subsurface settlement gauges were installed in the surrounding clay of the SDCM pile (S2 and S3), the DCM pile (S7 and S8) and in the unimproved clay (S5 and S6). Three piezometers were installed at 4.0 m depths from the original ground in the surrounding clay of SDCM pile (P1) and DCM pile (P3) and in the unimproved clay (P2). Four vertical inclinometer casings were installed. The vertical inclinometer casings were installed in the SDCM pile (I1), the DCM pile (I3), the surrounding clay of the SDCM pile (I2) and the surrounding clay of the DCM pile (I4).

Construction of Embankment
A 5 m high test embankment was constructed at the northern part of the Asian Institute of Technology (AIT) Campus, Thailand. The undrained shear strength of the uppermost 2 m thick weathered crust layer is significantly higher than that of the soft clay layer below. In order to obtain better deformation characteristics of the improved ground for both SDCM and DCM piles, a 1 m depth of weathered crust was excavated. Accordingly, prior to the embankment construction, a 21 m wide, 40 m long and 1 m depth foundation soil was removed. After the excavation of the trench, the area covered by the test embankment was backfilled with 1.0 m depth compacted silty sand. The silty sand was compacted to a unit weight of 17 kN/m³ by a vibratory roller. The area around the instruments was compacted by a vibratory hand compactor. Then, a 5 m high embankment was constructed with end slopes of 1:1 and side slopes of 1:1.5 with base dimensions of 21 m by 21 m and top dimensions of 9 m by 6 m (Figs. 9(a), (b)). The embankment material mostly consisted of weathered clay excavated from the area near the test embankment. The weathered clay was compacted to 0.30 m lift thickness to a density of 16 kN/m³. The embankment construction was completed within 30 days.

FIELD EMBANKMENT TEST RESULTS
Settlement Behavior of SDCM Pile and DCM Pile Improved Soft Clay Foundation
Figure 10 shows the settlements on top of the SDCM pile, the DCM pile, the surrounding clay of the SDCM pile, the surrounding clay of the DCM pile and on the surface of the unimproved clay during and after construction, and up to 570 days of full embankment loading. Approximately 50% of the total settlement occurred during the 30 days of construction of the test embankment. The settlement on the surrounding clay of the SDCM pile was slightly less than that on the surrounding clay the DCM pile. Thus, the embankment load was transferred to the SDCM pile more efficiently than to the
DCM pile. Moreover, the settlement on the SDCM pile is 40% less than the corresponding value on the DCM pile due to its higher stiffness. In addition, the settlements on top of the SDCM piles were almost 60% less than that of the unimproved ground.

Lateral Movements of SDCM and DCM Piles

The lateral movements of SDCM and DCM piles were obtained from inclinometers I1 and I3, respectively. The locations of the inclinometers are shown in Fig. 9(b). The comparison of the lateral movement profiles of the SDCM and DCM piles is shown in Fig. 11(a). About 65% and 55% of the total lateral movements occurred immediately after the construction of the test embankment for SDCM and DCM piles, respectively. Due to its higher flexural stiffness, the lateral movement in the SDCM piles was 60% that of the DCM pile.

The lateral movements of the surrounding clay adjacent to SDCM and DCM piles (Fig. 11(b)) were obtained from inclinometers I2 and I4, respectively, whose locations are indicated in Fig. 9(b). The measured maximum lateral movements at a depth of 1.0 m (excavation base level) immediately after embankment construction and after 570 days for the surrounding clay of the SDCM pile amounted to 18.3 mm and 28.3 mm, respectively, while those for the surrounding clay of the DCM pile amounted to 36.0 mm and 67.3 mm, respectively. Thus, about 65% and 50% of the total lateral movement occurred during the construction of the test embankment for the adjacent clays of the SDCM piles and the DCM piles, respectively. This indicates that the SDCM pile was capable of reducing the magnitude of lateral movement by 60%. Therefore, the SDCM and DCM piles were confirmed to move laterally together with their adjacent ground.

THREE-DIMENSIONAL FINITE ELEMENT SIMULATION

Finite Element Discretization

Finite element simulations were performed using the 3D FEM simulations developed by Brinkgreve and Broere (2006) since these allow for a realistic simulation of the construction sequences. The basic soil elements were represented by the 3D, 15-node wedge elements (6-node triangles in horizontal direction and 8-node quadrilaterals in a vertical direction). The axial compression and lateral simulation were consisted of an SDCM pile, a DCM pile and sub-soil foundations, as shown in Figs. 12(a) and (b). In Fig. 12(a), the finite element mesh, composed of more than 3,750 elements, is given, and in Fig. 12(b), the SDCM pile at the center of the model is shown. For the boundary condition, the bottom of model is fixed in all directions the surface is free in all directions. The vertical model boundary with their normal direction is fixed and the other directions are free (i.e., vertical model boundary in x-direction such as parallel to the y-z plane is fixed in the x-direction and free in the y and z directions). The DCM pile was modeled as volume elements capable of simulating the deformation and stresses. The prestressed concrete core pile inserted at the center of SDCM pile was modeled as a “massive pile”, and was composed of volume elements. Interface elements modeled with 16-node interface elements were assigned around the periphery of the concrete core. The interface elements consisted of eight pairs of nodes, each of which was compatible with the 8-noded quadrilateral side of the soil element. The distance between the two nodes of a node pair was zero. Each node had three translational degrees of freedom. Consequently, the interface elements allowed for differential displacement between the node pairs (slipping and gapping). Interface elements are required to have the strength reduction factors, $R_{int}$, which are the fraction of the surrounding soil strengths (cohesion and/or friction) effectively mobilized at the interface.

Material Models and Parameters

Although the prestressed concrete core pile has much higher strength and stiffness than the DCM pile, by 40 and 300 times, respectively, failure took place not only
Fig. 12. (a) Portion of 3D finite element model of pile test, (b) Portion of 3D finite element model of SDCM and DCM piles

Fig. 13. Effect of cohesion of DCM pile on axial compression load-settlement curve

within the DCM material (pile failure) but also in the concrete core piles (pile failure) especially during the lateral load tests. Consequently, the Mohr-Coulomb model (MCM) was used to simulate the prestressed core pile by referring to all the parameters from the compression test as well as the simulation in the PLAXIS 2D V8.5. The interface strength reduction factor of 0.4 obtained from the full scale pullout load test discussed earlier was used for the interface behavior between the core pile and the DCM material.

The Mohr-Coulomb model (MCM) was selected to model the behavior of the DCM piles. The vertical permeability of the DCM pile of 30 times that of the surrounding soil was based on the back-analysis using 2D PLAXIS software conducted by Lai et al. (2006). The backfill soil materials used in the embankment were compacted silty sand and weathered clay. The MCM was used to represent the compacted embankment materials, as tabulated in Table 2. The effective cohesion, friction angle and deformation characteristics of the backfill materials were determined from consolidated undrained triaxial (CIU) tests using representative specimens as well as the densities of the embankment materials. The MCM was used to model the weathered crust layer, medium stiff clay layer and stiff clay layer. The material properties were obtained from the previous test data on Bangkok clay (Balasubramaniam et al., 1978). The soft clay layer from 2 m to 8 m depth was modeled by the Soft Soil Model (SSM). The SSM is a Cam-clay type model developed by Vermeer and Brinkgreve, 1995. The material properties were obtained from the previous test data on Bangkok clay (Balasubramaniam et al., 1978) and the result of previous investigations (Chai 1992; Bergado et al., 1995; Bergado et al., 2002a, b). The FEM parameters for all the materials are also tabulated in Table 2.

Simulated versus Observed Data

Figure 13 shows the results of the simulations compared to the observed data when the cohesion of the DCM pile, $c_{_{DCM}}$, was varied from 100 to 300 kPa. The cohesion of the DCM pile significantly affected the ultimate bearing capacity of the DCM pile but the corresponding small effect on the SDCM pile implied that the core pile supported most of the load and transferred smaller proportions of the load to the tip of the core pile. For the axial compression of both DCM and SDCM piles, the effective cohesion, $c_{_{DCM}}$ of 200 kPa is the best fit to the measured data.

Using a 3D FEM simulation, the sensitivity analysis of the load-settlement curves of the SDCM pile was performed by varying the interface strength reduction factor, $R_{_{inter}}$. The shapes of the curves were affected by the $R_{_{inter}}$ values, as shown in Fig. 14. The $R_{_{inter}}$ values from 0.40 to 1.0 yielded slightly different load-settlement curves. However, the $R_{_{inter}}$ on 0.40 yielded good agreement between the observed and simulated data, thus con-
Fig. 14. Effect of Rinter on axial compression load-settlement curves for SDCM piles with 0.22 m square and 6 m long concrete core pile

Figure 15(a) shows the results of the simulation of the effect of the tensile strength of the DCM pile on the lateral load-displacement curve using the best fit parameter from the axial compression pile and comparing it with the observed data from the field test for DCM L-1. The additional parameter used for back analysis is the tensile strength of the DCM material. The tensile strength of the DCM material, TDCM, obtained from the laboratory testing by beam test was 150 kPa while the corresponding values from the lateral pile load test in the field were from 30 kPa to 60 kPa as shown in Fig. 16. Therefore, the simulation of lateral pile load test utilized varying TDCM from 0 to 75 kPa. The TDCM directly affected the yield points of the lateral load versus displacement curves. The higher the TDCM, the higher the ultimate lateral load. The appropriate TDCM is 50 kPa. The TDCM obtained from the simulation agrees with the TDCM derived from the lateral pile load test.

Figure 15(b) shows the results from the simulation compared to the observed data from the field test with SDCM of 0.22×0.22×5.5 m. The other parameter that

Fig. 15. Effect of tensile strength of DCM pile on lateral load-lateral displacement curve (a) DMC-L1 and (b) SDCM piles

Fig. 16. Mode of failure of DCM and SDCM piles under lateral loading tests
The tensile strength of the concrete core pile, $T_{\text{core}}$, is significant for the successful performance of the SDCM piles. The $T_{\text{core}}$, which varied from 4,000 kPa, 5,000 kPa and 6,000 kPa corresponding to 11%, 14% and 17% of the compressive strength of the concrete core pile (35,000 kPa). As shown in Fig. 15(b), the best fit parameter of $T_{\text{core}}$ is 5,000 kPa for all cases of the SDCM pile.

The 3D FEM model of the full scale test embankment is shown in Fig. 17(a) with 28,950 elements. Figure 17(b) shows that the DCM and SDCM piles beneath the embankment had the same element type and shared the same soil properties as the single pile (see Fig. 12(b)). The settlement versus time comparison between the observed and simulated data from the FEM analysis is plotted in Fig. 18. The settlements from the FEM analysis agreed well with the observed data with regard to both the settlement magnitudes and the settlement rates.

**Simulation of Sensitivity Analysis**

A sensitivity analysis was completed to determine the effect of the concrete core length on the ultimate bearing capacities by using different sectional areas as well as lengths of the concrete core pile in numerical experiments. In total, 28 simulations were performed by varying the concrete core pile lengths from 1 to 7 m and varying the sections of square concrete core pile from 0.18 m, 0.22 m, 0.26 m, and 0.30 m, respectively. The summary of the effect of the lengths and sectional areas on the bearing capacities is shown in Fig. 19. The results show that the length of the concrete core pile directly affects the ultimate bearing capacities. Increasing the lengths meant increasing the ultimate bearing capacities. On the other hand, an increase in the sectional areas did not have much impact on the bearing capacities.

The mode of failure of the SDCM and the DCM pile can be investigated by using a relative shear stresses function in 3D FEM simulations. The relative shear stresses give an indication of the proximity of the stress point to the failure envelope (Brinkgreve and Broere, 2006). It can be defined as the ratio of the shear stress divided by the shear strength. If the relative shear stresses equal 1.0, failure by shear will develop at this point. The comparison of the relative shear strength of the DCM pile and the SDCM piles is shown in Fig. 20. Similarly, at the ultimate load, the failure develops about 1 m below the top of the DCM pile and, in the case of SDCM piles, failure develops about 1 m below the tip of the 1 to 6 m long core piles. For the 7 m long core pile of the SDCM pile, the failure
took place at the underlying soil stratum. This means that the failure due to shear occurs at a depth of twice the diameter in the DCM pile and 1 to 6 m long core pile of SDCM pile. These failure modes from simulation are similar to the observed failure mode in the full scale tests reported by Zheng and Wu (2005). It can be concluded that, in the case of DCM pile and 1 to 6 m long core pile of SDCM pile, the failure developed at the unreinforced part or the DCM piles at about twice the diameter below the tip of core pile (DCM pile failure). On the other hand, in the case of 7 m long core pile in SDCM piles, the failure developed at the soil below SDCM pile (soil failure). Moreover, in the case of 6 m long core pile of SDCM piles, the failure occurred in both the soil and the DCM materials.

The axial load transfer along the pile lengths of the DCM and SDCM pile was different. For the DCM pile, the maximum load developed at the top 1 m and rapidly decreased until a depth of 4 m from the pile top and constant load of 10% of the ultimate load until the tip of the DCM pile (Fig. 21). Thus, the failure took place at the top in the case of DCM pile (see Fig. 1(a)). On the other hand, the axial load at the top of SDCM comprised 90% of ultimate load and linearly decreased to the pile tip, consisting of 70% and 30% of ultimate load and corresponding to 2 m and 7 m of concrete core pile length, respectively (Fig. 22).

A sensitivity analysis was done to determine the effect of the concrete core pile on the lateral loads by varying the lengths of concrete core pile from 0.5 to 6.5 m and also varying the sectional areas of core pile to 0.18 m, 0.22 m, 0.26 m and 0.30 m, as illustrated. These were the
same as those used in the axial compression pile test. The effects of the lengths on the ultimate lateral load of the SDCM pile are summarized in Fig. 23. It can be concluded that the results were similar for length of core pile longer than 3.5 m for all sectional areas.

The comparison between the FEM simulated results and the measured lateral displacement profile (Figs. 24(a, b)) showed lateral movement with depth. There were slight underestimations of the simulated results for the lateral displacements in DCM pile from 3 m to 8 m depth. The observed lateral movement profiles of SDCM pile were similar in shape to those of the DCM pile obtained from simulations immediately after construction until 570 days after construction.

CONCLUSIONS

This paper presents the observed and simulated results of the full scale embankment loading as well as full scale load tests on soft clay foundation improved by deep cement mixing (DCM) and stiffened deep cement mixing (SDCM) piles. The jet grouting method (jet pressure of 22 MPa) was utilized in the installation of DCM piles with a 0.6 m diameter. The SDCM is a reinforced DCM with a 0.22 m by 0.22 m precast concrete pile inserted at its center. The test results were simulated by a 3D finite element method (FEM) to back-analyze and confirm the related design parameters which were used further in the numerical experiments. Based on the results as well as subsequent analyses and FEM simulations, the following conclusions can be made:

1. By comparing the full scale axial compression load tests on the DCM and SDCM piles, the ultimate bearing capacity of SDCM piles with 0.22 m square and 6 m long concrete core pile can be improved by a factor of between 1.4 and 2 compared to the DCM piles. The low ultimate bearing capacities in the DCM piles can occur due to the non-uniformity of shear strength and the low quality control in the in-situ mixing during construction.

2. By comparing the full scale lateral load tests on the DCM and SDCM piles, the lateral ultimate bearing capacities of the SDCM piles can be increased by up to 15 times. The low lateral resistance of the DCM piles is due to its low flexural strength.

3. By comparing the full scale embankment load test on soft ground improved by the DCM and SDCM piles, the SDCM pile reduced the settlement by 40\% and lateral movement by 60\% compared to the DCM piles.

4. The strength reduction factor for interfaces, $R_{inter}$ of 0.40 was obtained from the full scale pullout interface test. Subsequent numerical simulations using the 3D FEM simulations for modeling the interface behavior between the concrete core pile and DCM material in SDCM pile confirmed this value.

5. The length of concrete core significantly affected the compression of SDCM pile. In contrast, the sectional area of concrete core only slightly affected the settlement of SDCM pile. The effective value of the length ratio ($L_{core}/L_{DCM}$) ranges from 0.57 to 0.85 for the compression of the SDCM pile.

6. Both the lengths and cross-sectional area of the SDCM piles influenced its ability to resist lateral pressure. The effective value of the length ratio ($L_{core}/L_{DCM}$) to resist lateral movement also ranges from 0.57 to 0.85.

7. From the test results and subsequent numerical experiments, including a sensitivity analysis using 3D FEM simulations, the superiority of the new technology called SDCM piles over the traditional technology of DCM piles has been confirmed.

NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$A_{core}$</td>
<td>section area of concrete core pile (m$^2$)</td>
</tr>
<tr>
<td>$A_{core}/A_{DCM}$</td>
<td>area ratio</td>
</tr>
<tr>
<td>$A_{DCM}$</td>
<td>section area of deep cement mixing pile (m$^2$)</td>
</tr>
<tr>
<td>$c_{soil}$</td>
<td>cohesion of soil (kPa)</td>
</tr>
<tr>
<td>$c_{DCM}$</td>
<td>undrained shear strength of deep cement mixing pile (kPa)</td>
</tr>
<tr>
<td>$c_{u,end}$</td>
<td>undrained cohesion of the soil at the bottom</td>
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</tbody>
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REFERENCES
