



Numerical simulations and parametric study of SDCM and DCM piles under full scale axial and lateral loads as well as under embankment load

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Although a Deep Cement Mixing (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. 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 (Fig. 1). 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 et al, 2005) and stiffened deep cement mixed (SDCM) column method (Wu et al, 2005).

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 using 3DFoundation software (Brinkgreve and Broere, 2006) 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 (Suksawat, 2009).

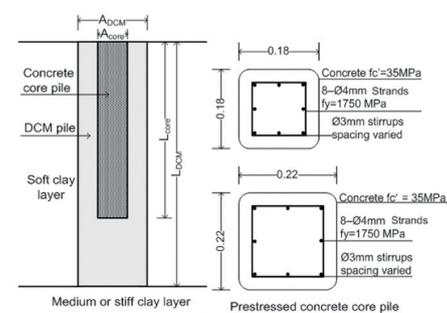


Fig. 1: (a) Schematic of SDCM pile
 (b) Details of prestressed concrete core piles

Materials	Depth (m)	Model	γ (kN/m^3)	Material behavior	E'_{ref} (kPa)	ν	λ^*	κ^*	c' (kPa)	ϕ' (deg)	OCR	Tensile strength (kPa)
Subsoil												
Weathered crust	0-2.0	MCM	17	undrained	2500	0.25			10	23		
Soft clay	2.0-8.0	SSM	15	undrained			0.10	0.020	2	23	1.5	
Medium stiff clay	8.0-10.0	MCM	18	undrained	5000	0.25			10	25		
Stiff clay	10.0-30.0	MCM	19	undrained	9000	0.25			30	26		
Foundation												
Concrete core pile		MCM	24	drained	2.8×10^7	0.15			8000	40		5000
DCM pile (with interface elements)		MCM	15	undrained	30000-60000	0.33			200-300	30		0-100
Concrete pile cap		LEM	-	non-porous	2.1×10^7	0.15						

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

SSM: soft soil model, MCM: Mohr-Coulomb model, LEM: linear elastic model



Project site and subsoil profile

The full scale axial and lateral pile load tests were performed by Shinwuttiwong (2007) and Jamsawang (2009) and the full scale embankment load test was conducted by Jamsawang et al (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 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 from the laboratory tests by compression test to be 35 MPa. Two lengths of 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 overestimated if the tensile strain is large enough to crack the concrete (Tand et al, 2008).

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/m³ of soil. 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 6m was utilized as shown in Fig.2. The arrangement of full scale pile load test consists of axial compressive pile (denote as C), lateral pile (L) and pullout (P) tests.

Axial compression pile load test

The axial compression pile tests were conducted on both the DCM and SDCM piles. The DCM piles have 0.60 m. diameter. The load was applied increasing at 10 kN interval until pile failure.

Lateral pile load test

The full scale lateral pile load tests were also conducted on designated SDCM piles. The horizontal load was applied at -0.30m from the top of pile with increasing lateral load until pile failure.

Embankment load test

The DCM pile consisted of 7m 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. Figures 3 show the plan layout of the embankment, respectively, together with the DCM and SDCM piles.

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 3DFoundation software. The soft soil model (SSM) was used for the soft clay layer and the Mohr-Culomb model (MCM) was used for the other elements including DCM and SDCM piles. The detail of model is illustrated in Fig. 4.

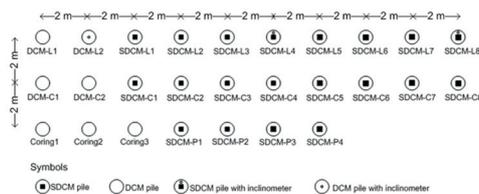


Fig. 2: Pile load test layout

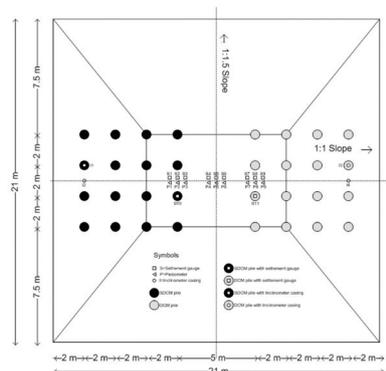


Fig. 3: Top view of the test embankment

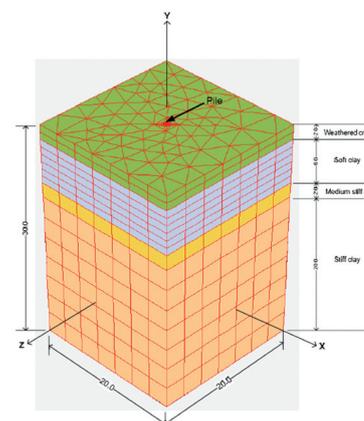


Fig. 4: Axial and lateral pile load test simulation model

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.

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

The embankment is supported by two types of piles consisting of the 16-SDCM piles and 16-DCM piles. 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 dimension from 0.22x0.22 to 0.30x0.30 m. The embankment discretization model using Plaxis Foundation 3D software is shown in Figs 5. The first phase was the initial stage that was setup as the in-situ state (k0 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 consolidation calculation was utilized in order to observe and compare with surface settlement at the top of SDCM, DCM and surrounding soil after 60, 90, 120, 150, 180, 240, 300, 360, 420, 510 and 600 days, respectively.

Results

Axial compression pile simulation

The appropriate parameters from back analysis for mixture of cement-clay cohesion in the DCM pile, CDCM, obtained from the 3D finite element simulations were 300 kPa and 200 kPa, respectively, as illustrated in Fig 6. 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 7. The slightly different results reflect the construction quality control in the field tests.

Figure 8 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 more effect than increasing the sectional area ratio, A_{core}/A_{DCM} .

Figure 8 shows the summary of the ultimate bearing capacity of SDCM pile. 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 9.

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, T_{core} , were evaluated in this study. The corresponding values for T_{core} and T_{DCM} obtained from the simulation were 5000 kPa and 50 kPa, respectively (Fig 10)

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 3.5m. (Fig 11)

The failure modes of SDCM pile can be divided into two categories, namely: short and long pile failures. Both failure categories depend on the length and the sectional area of concrete core pile. For the SDCM pile with concrete core piles longer than 3.5m, the failure occurred by bending moments (long pile failure). The SDCM piles with concrete core pile less than 3.50m, the failure occurred in the surrounding soil (short pile failure).

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 12 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 12. The parametric study was conducted by varying the sectional areas of the concrete core pile of 0.22 x 0.22m and 0.30 x 0.30m as well as varying the lengths of concrete core piles of 4, 5, 6 and 7m to study their effects on the embankment settlements. The effects of lengths and sectional areas of concrete core pile from simulation.

The length ratio, L_{core}/L_{DCM} , significantly affected the settlements of the SDCM piles while the area ratio, A_{core}/A_{DCM} , has only small effects on the settlements of the SDCM piles. The effects of lengths and sectional areas of the concrete core piles of SDCM piles on the ultimate settlement of embankment simulation are further illustrated in Fig 13. 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 6m and only slightly decreased from lengths of 6 to 7m. Moreover, the ultimate settlement only slightly decreased when increasing the sectional areas of the concrete core piles from 0.22 to 0.30m.

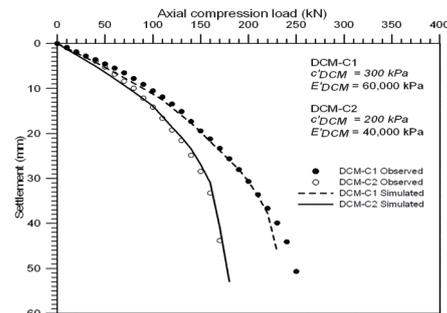


Fig. 6: Comparisons between observed and simulated axial compression load-settlement curves for DCM-C1 and DCM-C2

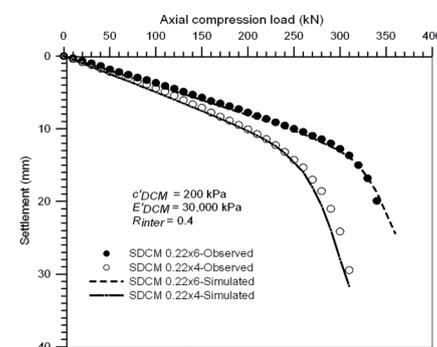


Fig. 7: Comparisons between observed and simulated axial compression load-settlement curves for SDCM

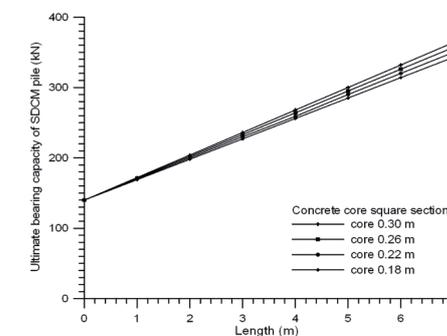


Fig. 8: shows the summary of the ultimate bearing capacity of SDCM pile

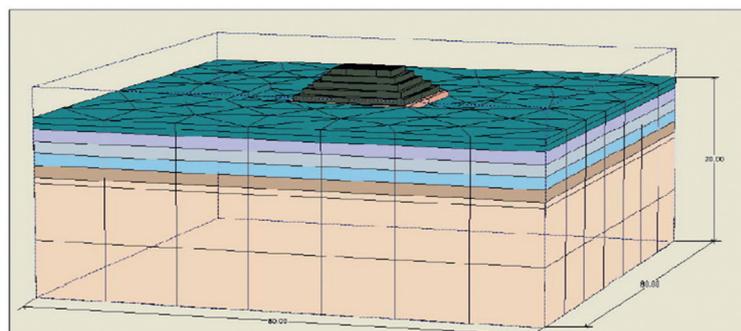


Fig. 5: Embankment simulation model

Conclusions

Increasing the length ratio, L_{core}/L_{DCM} , has more effect on the bearing capacity of SDCM pile than increasing the sectional area ratio, A_{core}/A_{DCM} . For the DCM pile, the maximum load developed at the top 1m and rapidly decreased until the depth of 4m from the pile top and constant load of 10% of the ultimate load until the tip of DCM pile. Thus, the failure takes place at the top in the case of DCM pile. The SDCM pile failure occurred in the unreinforced part (DCM pile failure) because the DCM pile is not strong enough to transfer load to the tip of DCM pile.

The ultimate lateral load of SDCM pile increased with increasing sectional area because it increased the stiffness of the pile but the length of concrete core pile did not increase the ultimate lateral load capacity when using the lengths longer than 3.5m. For the SDCM pile with lengths longer than 3.5m, the failure occurred by bending moment (long pile failure) while the short pile failed by surrounding soil failure. The longer core pile can reduce the vertical displacement and increased the bearing capacity of SDCM pile. The length and cross-sectional area of concrete core pile of SDCM pile significantly affected the lateral movement of the embankment

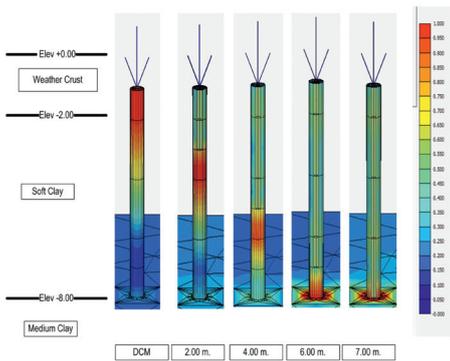


Fig. 9: Relative shear stresses of 0.22 x 0.22 m core piles at failure load from simulations

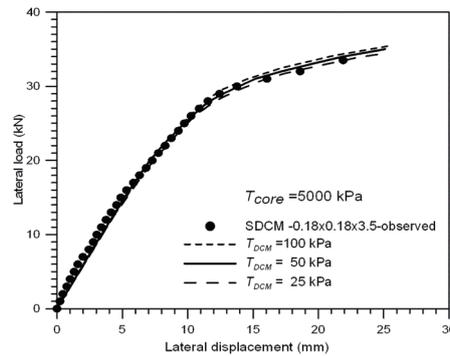


Fig. 10: Comparisons between observed and simulated lateral piles load-settlement curves for SDCM

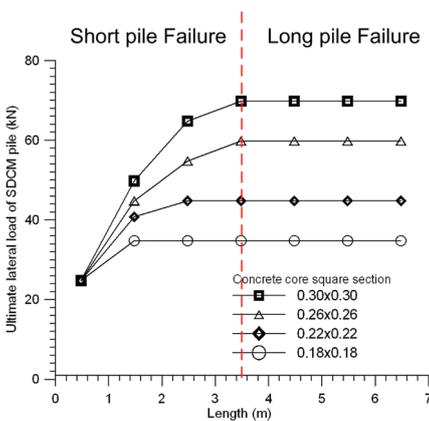


Fig. 11: Effect of lengths and sectional areas of concrete core piles on the ultimate lateral load of SDCM pile

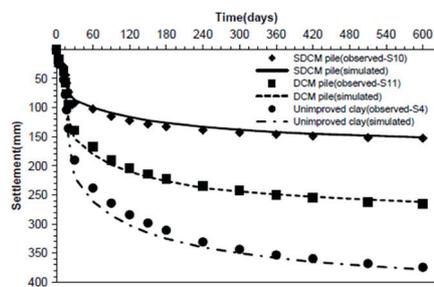


Fig. 12: Comparison of observed and simulated surface settlements

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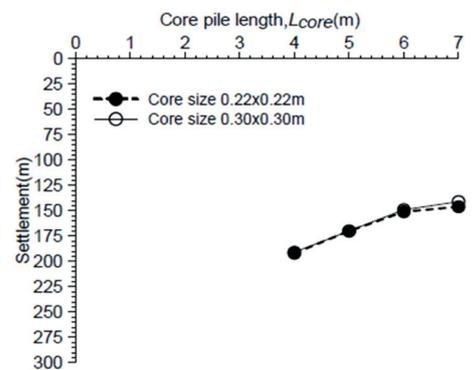


Fig. 13: Effect of lengths and sectional areas concrete core pile on ultimate settlements of SDCM pile