Performance of Reinforced Cement Columns to Resist Lateral Load for Stabilization of Soft Soil Slopes

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ABSTRACT: Improved lateral capacity of cement columns with concrete core insertion was investigated. The column, called Stiffened Deep Cement Mixing (SDCM) pile, is introduced to mitigate problems related to low flexural resistance as well as defects from non-thoroughly mixing of normal cement columns. Results from a full-scale load test show that lateral capacity of 600-mm-diameter cement columns in Bangkok clay are increased by 10-15 folds with insertion of 180-mm and 220-mm square concrete piles. In addition, the insertion helps increase the lateral displacement of the column heads at peak resistance from 3-4 mm to 15 mm, i.e. the column behavior becomes more ductile. 3D FEM simulations using Plaxis 3D Foundation are conducted to back calculate relevant parameters such as clay-cement mix cohesion, C_{DCM} and modulus, E_{DCM} which are found to be 200 kPa and 30,000 kPa, respectively. A sensitivity analysis shows that sectional area ratio, A_{core}/A_{DCM}, significantly influences ultimate lateral resistance while length ratio, L_{core}/L_{DCM}, is not always. When the length of concrete pile insertion is longer than 3.5 m, no improvement is observed. In addition, tensile strength of DCM, T_{DCM}, and that of concrete core pile, T_{core}, are very important factors.

1 INTRODUCTION

Various methods of in situ soil mixing with chemical additives are available for improvement of mechanical properties of soft soil foundation. The soil mixing has been used for many diverse applications including building and bridge foundations, retaining structures, liquefaction mitigation, temporary support of excavation and water control. The techniques, which were originally introduced about 50 years ago in USA, Scandinavia and Japan, have been increasing used and now gained popularity worldwide. In a broad category there are two principal methods of treatment, namely high pressure jet grouting and low pressure mechanical mixing. The former utilizes high pressure water jet in cutting and mixing soil with additive while in the latter the in situ soil is mixed with an additive by means of mixing blades. Names such as Jet Grouting, Soil Mixing, Deep Cement Mixing (DCM), Jet, Deep Soil Mixing, (DSM), Dry Jet Mixing (DJM), and Lime Columns are known to many. Each of these methods has the same basic root, finding the most efficient and economical method to mix additive with soil and cause properties of soils to become more like properties of soft rocks. Several stabilizing agents can be utilized such as lime, fly ash, and cement. The most common is cement.

In Thailand, firstly Jet Grouting was introduced about 20 years ago to aid deep excavations for basement construction of buildings in Bangkok soft soil. It was shortly followed by the introduction of DCM method in the excavation of basement and foundations of the SCB Park complex project. The mixing products were referred to as “Cement Columns or Soil Cement Columns” which had configuration similar to bored piles. The method was then adopted by the Department of Highways of Thailand for road construction in the soft soil terrain of Bangkok to solve problems of instability and excessive settlement of fill embankment (Phienwej and Taesiri, 1996). The method has proven be so efficient, thus it becomes one of the popular methods in construction of road embankments on soft soils. Even though, cement columns are commonly constructed by means of the Deep Cement Mixing method, the Jet Cement Grouting method can also be used. Their products essentially have similar mechanical properties.

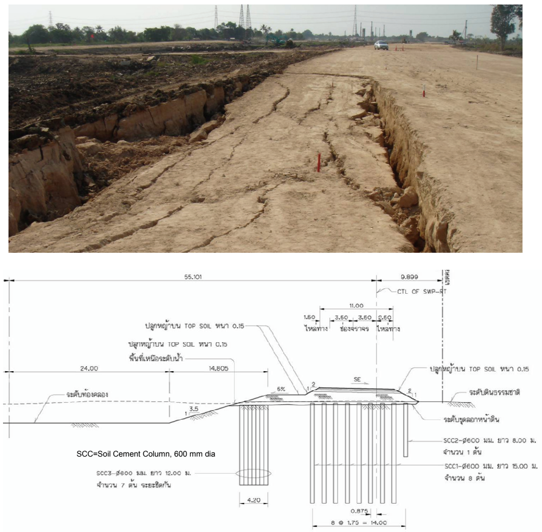

Figure 1: An example of problematic application of cement columns in stabilizing slope in soft Bangkok clay.

Although Soil Cement Column has proven to be effective in capturing settlement of roadways and light foundations, its application in slope stabilization and deep excavation is often plagued with stability problems. Although the soil cement mix may be strong in compression and shear, it is brittle thus very weak in tension or flexural resistance. Therefore, in slopes or deep excavations cement columns are subjected to lateral forces, which would result in deflection and bending stress that could easily crack the columns in flexural tension before its shear strength could be fully mobilized for shear slip resistance to slope movement. In such a case the cement columns often failed prematurely, especially when they are placed in the configuration of “column type”- single column at a systematic spacing. Moreover, unexpected lower strength than the design value could also be anticipated when quality control during construction was not sufficiently exercised. This even makes the column very weak in flexure bending. Such unfavorable situations have occurred in numerous projects in the application of cement columns in Bangkok soft soils, ranging from roadways construction along canal, excavation of water diversion or conveyance canals, pond excavations, deep excavation pits, etc. An example of such a case is shown in Figure 1. To minimize the problem, the “Wall type or Block type” of cement column arrangement configuration may be employed, which can help minimize flexural tensile stress by increasing section modulus of the soil-cement mix zone. However, the approach may not totally solve the problem of weakness of cement column owing to defects stemmed from inappropriate quality control during construction.

Another alternative is by adding a thick slab of soil-cement mix to cap column-type cement columns at the head (Sam et al, 2008), which makes them act as a group not individual column. Its configuration and behavior are similar to the relief platform retaining structure for which a part of vertical load is transferred to deeper soil level (see Figure 2). However, these approaches can lead to a substantial increase in amounts of cement columns which could make the methods less competitive to others, such as reinforcement by mechanical structures or sheet walls.

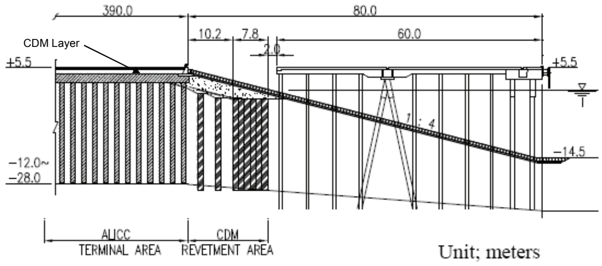

Figure 2: Use of CDM layer to improve lateral resistance of DCM piles in port construction in soft deltaic clay (after Sam et al, 2008).

Another measure is to reinforce cement columns with a ductile core insertion. Steel I-beam or pipe reinforcement is placed in DCM excavation support walls in order to resist bending moment (Rutherford et al., 2007). The typical arrangement of DCM excavation support walls is shown in Figure 3.

The method is commonly adopted in few countries, including Japan and USA. However, it can be very expensive owing to the high cost of steel. Thus its use may be limited to some certain circumstances, especially in countries such as Thailand where cost of structural steel is relatively much higher than other cement. The alternatives of insertion reinforcement would be timber pile or reinforced concrete pile. The former has ductile behavior that is suitable to resist flexural bending but it has durability constraints. Whereas concrete is a brittle material, its flexural resistance may be improved by rebar reinforcement.

In this preliminary study, effectiveness of reinforced concrete pile as core insertion in improvement of lateral capacity of cement columns in soft Bangkok clay is investigated. To differentiate it from normal cement column constructed by means of the DCM method, the composite pile is referred to as “Stiffened DCM (SDCM)” cement column. This composite column is composed of an inner precast concrete pile hereinafter called concrete core insertion and an external DCM pile.

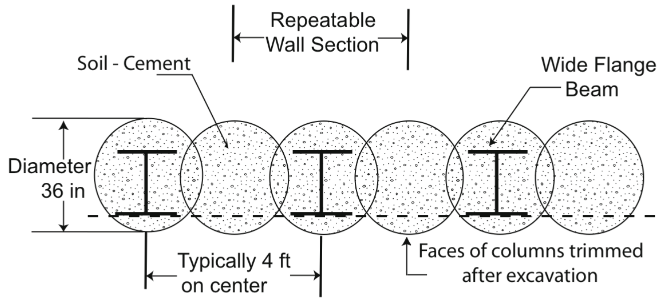

Figure 3: Typical arrangement of DSM columns. (Rutherford et al., 2007).

2 STIFFENED DEEP CEMENT MIXED (SDCM) PILES

Stiffened Deep Cement Mixed (SDCM) piles are a composite structure of concrete pile and deep cement mixed pile as shown in Figure 4. A pre-stressed concrete core pile is inserted into the center of a cement column immediately after its construction by the wet mixing method. In the SDCM pile, the DCM pile forms the surrounding outer layer supporting the concrete core pile. 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 method of improving the capacity 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 DCM pile used in this study was constructed by wet mixing method with 600 mm in diameter and 7.0 m in length. The Stiffened Deep Cement Mixing (SDCM) pile has core insertion to enhance its flexural and axial stiffness. Pre-stressed concrete pile is chosen in this study because it is cheaper than the steel pile. Moreover, its quality is superior to timber pile from strength and durability point of view.

3 SUBSOIL PROFILE

A full scale axial and lateral pile load test program was performed by Shinwuttiwong (2007) and Jamswang et al (2009) on campus of Asian Institute of Technology (AIT). The site is situated in the Bangkok plain that is famous for its thick layer deposit of marine soft Bangkok clay. The subsoil and their properties at the site are shown in Figure 5. 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 50 kPa. Soil parameters are shown in Table 1.

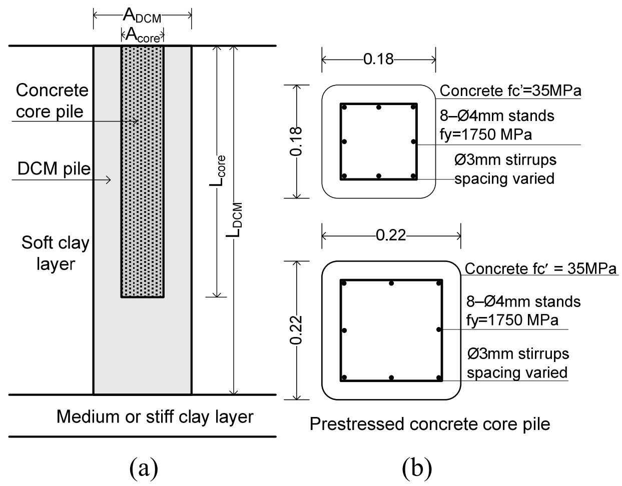

Figure 4: (a) Schematic of SDCM pile (b) Details of pre-stressed concrete core piles.

The compressive strength of the concrete core pile was 35 MPa. Two lengths of the core pile were used in the field test, i.e. 3.5 m and 5.5 m. However, for the numerical simulation the length of the concrete pile was varied from 1.0 m to 7.0 m with 1.0 m increment to evaluate the effect of the length of the core insertion on the capacity of the SDCM pile. The Mohr-Coulomb model was used to simulate concrete core pile instead of linear elastic model because the stiffness can be overestimated if the tensile strain is large enough to crack the concrete (Tand and Vipulanandan, 2008).

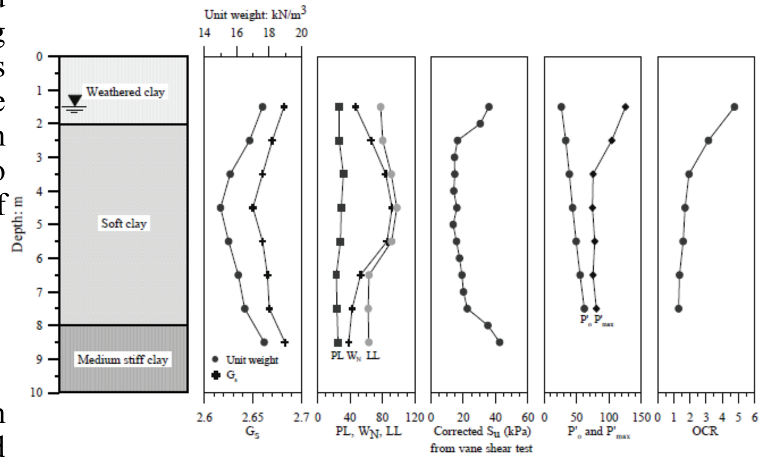

Figure 5: Subsoil profile within the campus of AIT.

4 FULL SCALED LATERAL CAPACITY

The DCM pile was constructed by Deep Mixing cement dosage of 150 kg/m3 of soil. The full scaled pile load test program consisted of 8 SDCM and 2 DCM piles.

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

The ultimate lateral capacity of SDCM piles with 180 mm square core insertion with length of 4 m and 6m was 33.0 kN and 34.5 kN, respectively, while the capacity of piles with 220 mm square core insertion of length of 3.5 m and 5.5 m were 44.5 kN and 45.5 kN, respectively. On contrary, the maximum lateral capacity offered by DCM piles (without core insertion) was only in the range of 2.5-3.5 kN. The ultimate lateral capacity of SDCM piles increase 10 and 15 time of DCM pile for 180 mm and 220 mm reinforced concrete core insertion, respectively. Furthermore, the ultimate lateral displacement significantly increases from 2 mm to 12-14 mm, as illustrated in Figure 6. The result indicated that the length of concrete core pile for the range used in the test i.e. 4-6 m did not affect much the lateral capacity. However, the section area of the concrete core affects did has a noticeable effect.

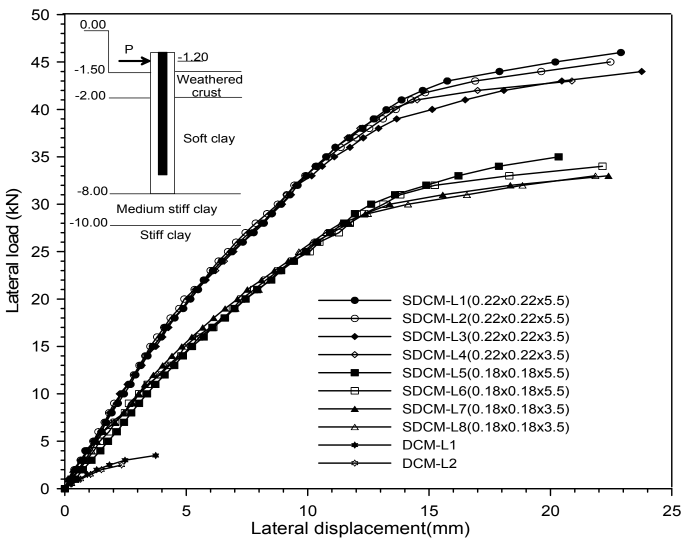

Figure 6: Lateral load-lateral displacement results from filed tests

For reference, the result of axial load test on the SDCM full scaled test program is also shown in Figure 7. It can be seen that the concrete core insertion also help improve axial capacity of the cement column. This is owing to the fact that the structural capacity of the pile, not the soil capacity, which governs the overall capacity of cement column was improved.

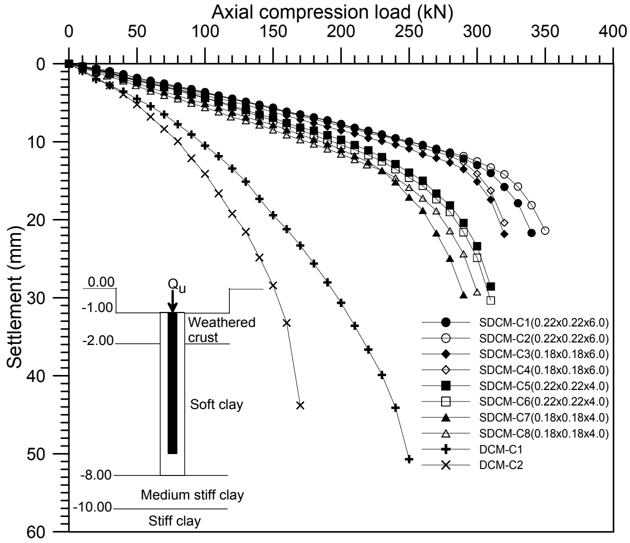

Figure 7: Test results on axial load-settlement of SDCM piles.

5 FEM SIMULATION OF LATERAL RESISTANCE OF SDCM

The lateral pile load tests of SDCM are simulated using PLAXIS 3D Foundation software (Suksawat, 2008). The mesh consisted of 15-node wedge elements. These elements are composed of the 6-node triangular faces in the x-z planes, as generated by the 2D mesh generation, and 8-node quadrilateral faces in the y-direction. The simulation model used is shown in Figure 8.

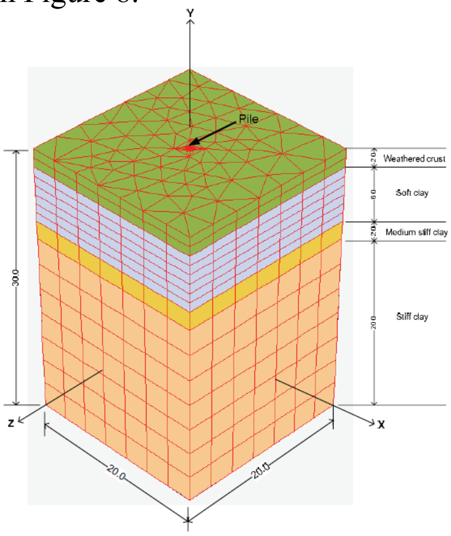

Figure 8: Axial and Lateral pile load test simulation model.

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 1.5m of the soil. In the subsequent stages, a pile cap was added to distribute the load.

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

Materials		Model	γ (kN/m^3)	Material behavior	E'_{ref} (kPa)	ν	λ^*	κ^*	c' (kPa)	ϕ' (deg)	OCR	Tensile strength (kPa)
Subsoil	Depth(m)											
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	2.8x10^7	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	2.1x10^7	0.15						

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

After the addition the pile cap, the loading of the piles is commenced. The horizontal load is increased in interval of 5 kN until failure is reached.

6 FEM RESULTS

The back-calculated values for mixture of claycement cohesion in the DCM pile, C_{DCM}, and modulus, E_{DCM}, obtained from the 3D finite element simulation were 200 kPa and 30,000 kPa, respectively. In addition, tensile strength of DCM pile, T_{DCM}, and of concrete core, T_{core}, were also evaluated. It was found that T_{DCM} of the two tested DCM pile were 50 kPa and 25 kPa and the corresponding values for T_{core} was 5000 kPa. (Figures 9 & 10).

The ultimate lateral load of SDCM pile increased with increasing sectional area of the concrete core insertion. The increasing length of the core also helped improved the lateral capacity of SDCM but the effect ceased when the length reached a certain threshold value. For the condition of SDCM and soil simulated the length of concrete core pile did not further increase the ultimate lateral load capacity of SDCM when it exceeded 3.5m. (Figure 11)

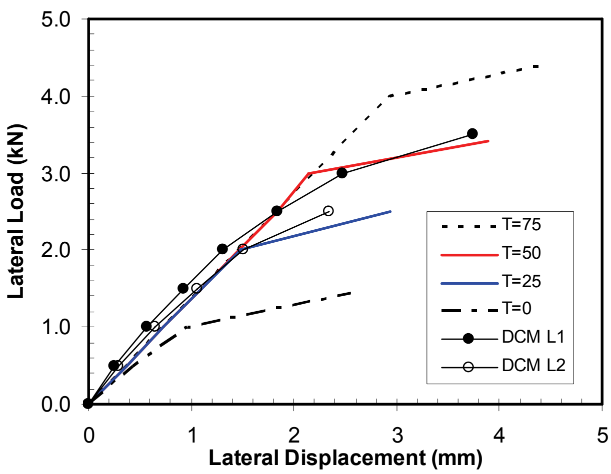

Figure 9: Comparisons between observed and simulated lateral load –settlement curves for DCM-L1 and DCM-L2.

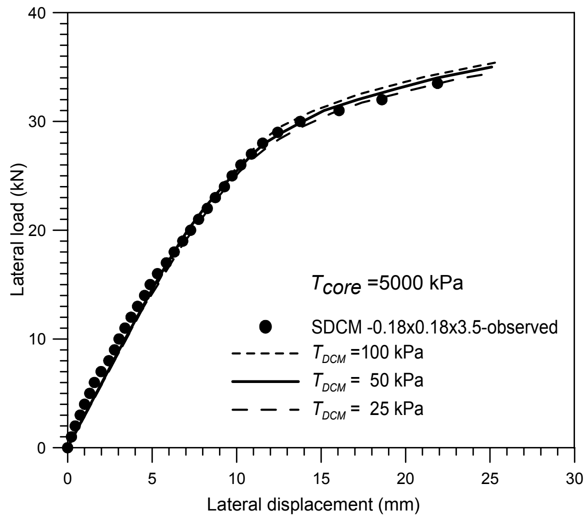

Figure 10: Comparisons between observed and simulated lateral piles load –settlement curves for SDCM.

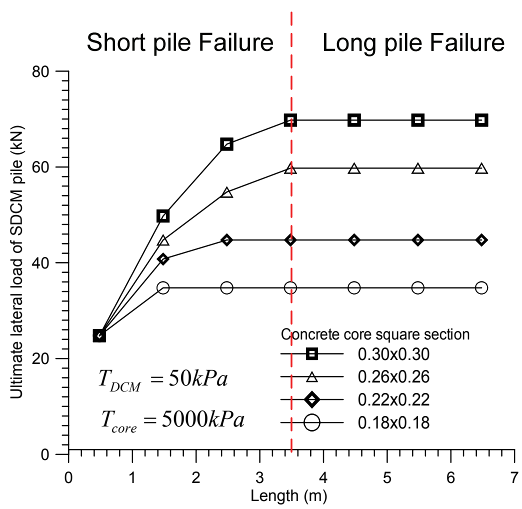

Figure 11: Effect of lengths and sectional areas of concrete core piles on the ultimate lateral load of SDCM pile.

Figure 12 shows the failure mode of DCM pile caused by the bending moments. 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).

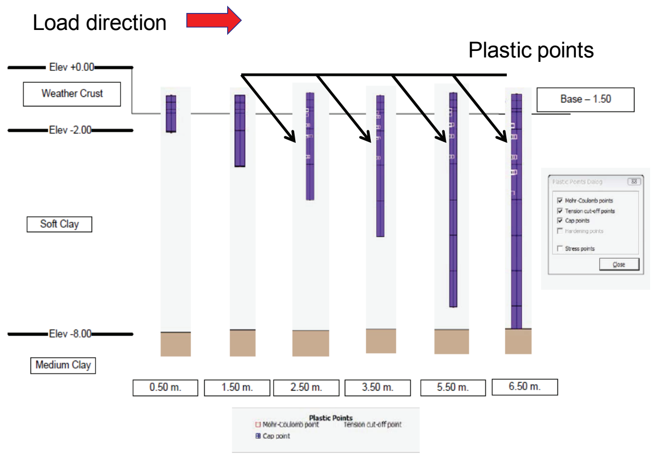

Figure 12: Mode of failure of SDCM pile with 0.22x0.22m core pile under lateral loading from simulations.

7 LATERAL CAPACITY OF SDCM WITH TIMBER PILE INSERTION

FEM analysis is also made to evaluate effectiveness of timber piles as core insertion for DCM in Bangkok. The timber pile has potential application due to its readily availability and low cost. When the pile is completely surrounded by soil-cement mix, the durability problems of decaying should be of a concern. The results of the analysis in term of load settlement curves of the SDCM piles reinforced with 7-inch, 8-inch and 10 inch diameters with length of 5 m are summarized in Figure 13. The assumed properties of the piles tensile and compressive strength are 12 MPa and modulus of elasticity is 12 GPa.

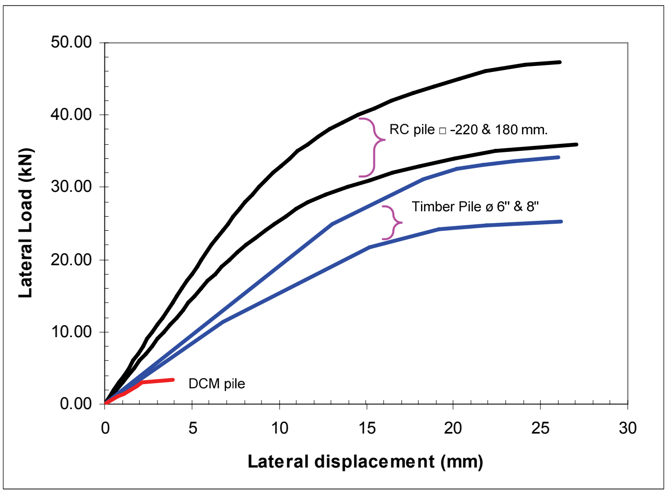

Figure 13: Comparisons of reinforced concrete, timber core piles and DCM piles on lateral pile load –displacement curve.

Figure 13 illustrated the comparison of RC, timber core piles and DCM piles on lateral load-displacement curve. It can be obviously seen that timber core pile of 8” diameter and RC pile of 0.18 m core size show the similar ultimate lateral loads. The displacement at the peak lateral resistance of the timber piles of 8” in diameter was higher because the timber piles have more ductile property than RC piles. In addition, the higher flexibility of timber piles can be facilitated to improve the stability of embankment. Moreover, the construction cost of timber pile is only a one third of the RC pile approximately.

8 CONCLUSIONS

The full scaled load test program and 3D FEM analysis conducted in this study showed that core insertion of cement column constructed in Bangkok soft clay can significantly increase lateral capacity of the column which is called Stiffened Deep Cement Mixing (SDCM) pile. This is crucial for use of cement columns in improvement of stability of slope or excavation. The core insertion also helps improve the axial capacity of the column.

For the tested SDCM piles, it was found that the lateral capacity of 600-mm-diameter cement columns were increased by 10-15 folds with insertion of 180-mm and 220-mm square concrete piles. The lateral displacement of the column heads at peak resistance increased from 3-4mm to 15mm, i.e. the column behavior becomes much more ductile which was desirable to slope reinforcement.

The ultimate lateral load of SDCM pile increased with increasing sectional area of the core insertion because it increased the flexural stiffness of the pile. However, the effectiveness of the length increase of the core insertion cease when the length exceeded a threshold value of 3.5m for the condition in the test program.

The failure modes of SDCM pile in lateral loading can be divided into two categories, i.e. short and long pile failures. Both failure categories depended on the length and the sectional area of concrete core pile. For the SDCM piles with length longer than 3.5m, the failure occurred by flexural failure (long pile failure) while short piles failed in surrounding soil failure mode.

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