

PERFORMANCE OF AN SDCM COLUMN-SUPPORTED EMBANKMENT

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Received: April 08, 2018; Revised: May 14, 2018; Accepted: May 18, 2018

Abstract

The stiffened deep cement mixing (SDCM) column uses a precast concrete core inserted at the center of a DCM column. This research presents the full-scale behavior of a test embankment built on a soft clay deposit improved by using both DCM and SDCM columns in Bangkok, Thailand. A 0.22 m square and 6 m long concrete pile was selected as a stiff core to create the SDCM column for this study. Both SDCM and DCM columns were subjected to axial compression and lateral load tests to determine the vertical and lateral loads, respectively. A three-dimension finite element analysis was performed to determine the axial load and bending moment in the DCM and SDCM columns. In addition, a stability analysis was also conducted to calculate the factor of safety against the slope failure. The major findings show that the lateral ultimate bearing capacity of the SDCM column and the displacement of improved ground with the column under the embankment loading can be improved by factors of 13 and 1.8, respectively, compared to the DCM column.

Keywords: Deep mixing, embankment, SDCM column, simulation, soil stabilization

Introduction

A deep cement mixing (DCM) column is often used to increase the bearing capacity of a soft soils' foundation and to reduce settlements of full-scale embankments (Lai *et al.*, 2006; Jamsawang *et al.*, 2016). However, DCM

columns have low strength and stiffness, specifically, their flexural strength (Dong *et al.*, 2004; Jamsawang *et al.*, 2011) leading to a low bearing capacity and large settlements (Wu *et al.*, 2005). To improve the properties of

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DCM columns, the stiffened deep cement mixing (SDCM) column was introduced because it has higher strength and stiffness and can sustain a higher bending moment and resist higher lateral loads. The SDCM column employs a precast reinforced concrete pile inserted at the centre of a DCM column, and the cost of the SDCM column is only 1.1 times higher than the DCM column.

A number of field studies have been reported on the use of DCM column-supported embankments, such as Lai *et al.* (2006), Hello and Villard (2009), Liu *et al.* (2012), Nunez *et al.* (2013), Zhang *et al.* (2014), Liu *et al.* (2015), and Lu and Miao (2015). A limited field report on SDCM column-supported embankments has been presented. This paper presents the full-scale load tests on SDCM and DCM columns in soft Bangkok clay under axial compression and lateral loads. Moreover, a 5 m high embankment on an SDCM column was constructed on soft Bangkok clay improved with both SDCM and DCM columns, in order to compare their performances under working stress levels.

Full-Scale Tests on SDCM and DCM Columns

Test Site and Soil Condition

The test site was located at the northern part of the campus of the Asian Institute of Technology (AIT) in Klong Luang, Pathumthani, Thailand. The uppermost soil layers that are 10 m thick can be divided into 4 layers. The weathered crust forms the uppermost layer consisting of weathered clay forms in the uppermost 2 m underlain by a soft clay layer down to about 6 m depth. The medium stiff clay layer was found at 8 to 10 m depth. Below this layer is a stiff clay layer. The undrained shear strength obtained from a field vane test of the soft clay was 16 to 17 kPa. Underlying the soft clay layer is a medium stiff clay layer, having strength of more than 30 kPa.

Construction of DCM and SDCM Columns

DMCs were installed down to the bottom of the soft clay layer by the jet mixing method

employing a jet pressure of 22 MPa. The water-cement ratio (W/C) of the cement slurry and the cement content employed for the construction with the DMCs were 1.5 and 150 kg (m³ of soil), respectively. Each DMC has a diameter of 0.6 m and length of 7 m. The SDCM column was constructed by insertion of a 0.22 m square and 6 m long concrete pile right away after the deep cement mixing had been completed. The core samples of the DCM columns were extracted for unconfined compression tests in the laboratory. The values of the unconfined compressive strength (q_u) ranged from 500 kPa to 1,500 kPa with the average value of 1,000 kPa while the modulus of elasticity (E_{50}) ranged from 50,000 kPa to 150,000 kPa with average value of 100,000 kPa indicating an empirical relationship of $E_{50} = 100q_u$.

Axial Compression Load and Lateral Load Tests

The axial compression tests were performed in accordance with ASTM D-1143. The load was applied in increments of 10 kN. Each load increment was maintained for 5 min. The load was applied until continuous vertical displacements occurred at a slight or no increase in load. The lateral load tests were performed in accordance with ASTM D-3966. The load was applied in increments of 0.5 kN and 1 kN for the DCM column and SDCM column, respectively. Each load increment was maintained for 10 min. The load was applied until continuous lateral displacements occurred at a slight or no increase in load.

Embankment Load Test

Construction of Foundation Improvement and Field Instrumentation

Prior to the embankment construction, the foundation subsoil was improved with SDCM and DCM columns, which were installed in situ by the jet mixing method employing a jet pressure of 22 MPa. Both the SDCM and DCM columns were installed at 2 m spacing as shown in Figure 1(a) and 1(b). Figure 1(a) and 1(b) also shows the instrumentation in plan and cross-section views, respectively. The surface settlement plates were installed on the top of

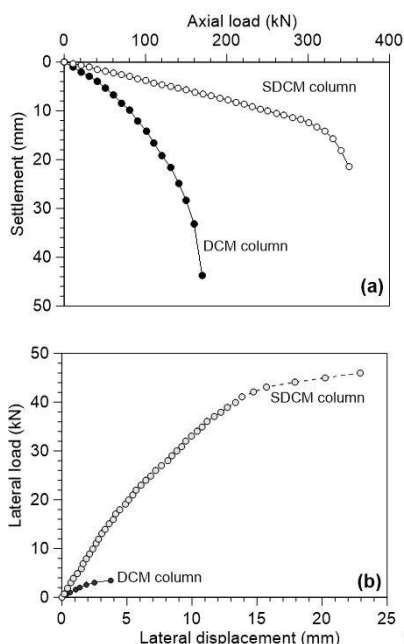


Figure 1. (a) axial load versus settlement curves and (b) lateral load versus lateral displacement curves for SDCM and DCM columns obtained from field load tests

the SDCM column (S1) and DCM column (S3), and on the unimproved clay (S2) to measure the settlement. The vertical inclinometer casings were installed in the SDCM column (I1) and, DCM column (I2) to observe the lateral movement with depth.

Construction of Embankment

Prior to the embankment construction, the foundation soil was removed to a width of 21 m, length of 40 m, and depth of 1 m. After the excavation of the trench, the area covered by the test embankment was backfilled with 1 m depth of compacted silty sand. The silty sand was compacted to a unit weight of 17 kN/m^3 with a vibratory roller. 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. The embankment material mostly consisted of weathered clay

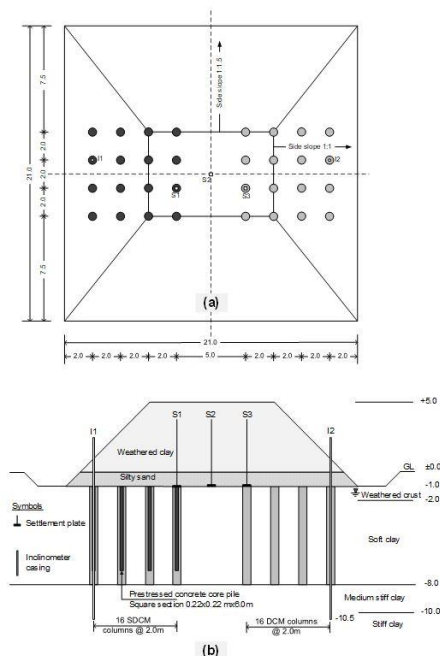


Figure 2. (a) plan view and (b) section view of the test embankment built on SDCM and DCM columns

excavated from the area near the test embankment.

Full-scale Load Test Results

Figure 2(a) shows the axial compression load versus settlement relationships for the DCM and SDCM columns. An ultimate vertical load was determined by the slope tangent method at the point of intersection of the initial and final tangents to the load settlement curve. The ultimate vertical loads were 140 and 320 kN for the DCM and SDCM columns, respectively. Figure 2(b) presents the lateral load versus lateral displacement curves for the DCM and SDCM columns. The ultimate lateral loads of the DCM and SDCM columns were 3.5 and 45 kN, respectively. Excavation after the test revealed cracks of the DCM and SDCM columns below the ground surface. This means that the failure mode was column body failure due to bending moment induced by the lateral

load. The ultimate bending moments for the 0.6-m-diameter DCM column and 0.22-m-square concrete pile are 3.4 and 19 kN-m, respectively, which were calculated from the flexural tests in the laboratory.

Full-Scale Embankment Test Results

Settlement

Figure 3 shows the settlements on top of the SDCM column and DCM column and on the surface of the unimproved clay obtained from surface settlement plates S1, S3, and S2, respectively, during and after construction up to 570 days of full embankment loading. After embankment construction, the total settlements on the SDCM column, DCM column, and on unimproved clay amounted to 92, 149, and 186 mm, respectively. The maximum settlements on the SDCM column, DCM column, and unimproved clay amounted to about 153, 265, and 374 mm, respectively, at 570 days after embankment construction. Approximately 50% of the total settlement occurred during the 30 days' construction of the test embankment. The embankment load has been transferred to the SDCM column more efficiently than to the DCM column. Moreover, the settlement on the SDCM column is 40% less than the

corresponding value on the DCM column due to its higher stiffness. In addition, the settlements on top of the SDCM column was almost 60% less than that of the unimproved ground while that of the DCM column was only 30% less than that of the unimproved ground.

Lateral Movement of SDCM and DCM Columns

Lateral Movement Profile

The comparison of the lateral movement profiles of the SDCM and DCM columns after embankment construction, at 90 and 570 days after construction are plotted in Figure 4(a). The measured maximum lateral movements at a depth of 1 m, or at the column head, immediately after embankment construction and after 570 days for the SDCM column amounted to 19.9 and 29.6 mm, respectively, while the corresponding values for the DCM column amounted to 38.7 and 70.2 mm, respectively. Thus, about 65% and 55% of the total lateral movements occurred immediately after construction of the test embankment for the SDCM and DCM columns, respectively. Due to its higher flexural stiffness, the lateral movement in the SDCM column was 60% less than that in DCM column.

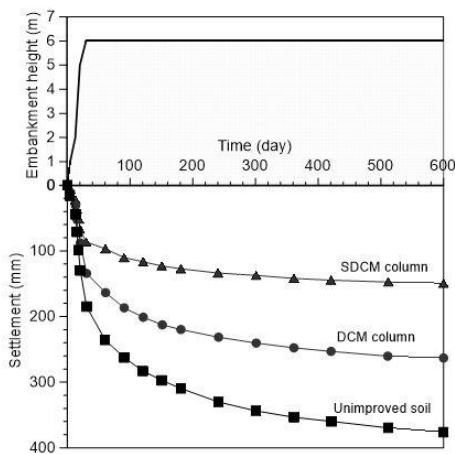


Figure 3. Settlement versus time curves obtained from field embankment tests

Ratio of Lateral Movement to Surface Settlement

The ratio of maximum lateral movement to maximum surface settlement was used as the criterion for safety control during embankment construction. The ratio of lateral movement to surface settlement is defined as the maximum lateral displacement at the toe to the maximum settlement at the center line of an embankment. A small value of the ratio is necessary to maintain the stability of the embankment over the subsoil. As an embankment approaches failure, the lateral movement to settlement ratio increases rapidly. At the embankment failure, the value is typically larger than 0.5.

Figure 4(b) shows the measured lateral movement- settlement ratio versus the time

curve during embankment construction until 570 days after construction of the SDCM and DCM columns. The measured SDCM column, surrounding clay of the SDCM column, DCM column, and surrounding clay of the DCM column show the similar trends that the ratios decreased from the embankment height of 1 m to the embankment height of 2 m and then increased until the embankment height of 6 m and decreased with time until at 240 days or 210 days after construction and became constant implying that both vertical settlements and lateral movements increased slowly at a similar rate. The maximum ratios are 0.23 and 0.30 for the lateral movement to settlement

ratios of the SDCM and DCM columns, respectively, occurring during embankment construction to 30 days after embankment construction. The ratios became constant at 240 days or 210 days after construction and amounted to 0.19 and 0.25 for the SDCM and DCM columns, respectively. Thus, the maximum ratios are still less than 0.5 and the ratio of the SDCM column are less than that of the DCM column. Therefore, the SDCM column increases the stability and safety during construction.

Three-Dimensional Finite Element Analysis

Finite Element Discretization

Finite element simulations were performed using the software PLAXIS 3D Version 2017. The software was used to calculate the bending moment in the SDCM and DCM columns, and the factor of safety against slope failure of the foundation soils improved with SDCM and DCM columns under the embankment load. The 3D finite element model consisted of the embankment, SDCM column, DCM column, and foundation soil as illustrated in Figure 5, which shows the finite element mesh consisting of more than 100,000 elements.

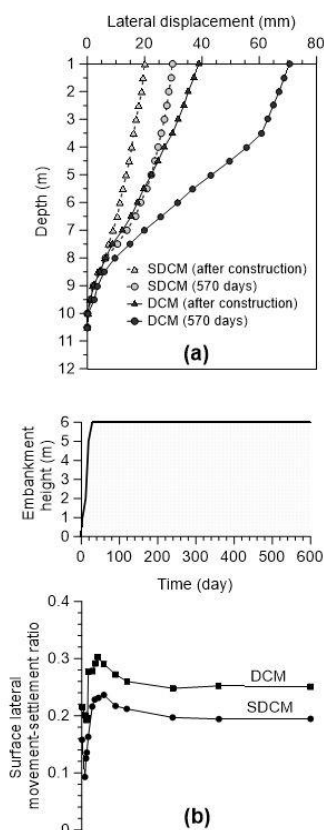


Figure 4. (a) lateral displacement profiles for SDCM and DCM columns (b) surface lateral movement-settlement ratio versus time curves obtained from field embankment tests

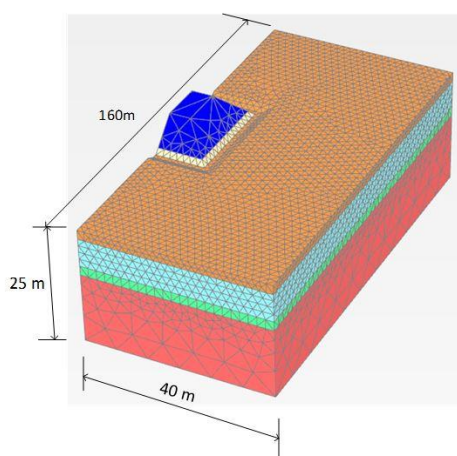


Figure 5. Three-dimensional finite element mesh of field embankment tests

Table 1. Parameters used in Mohr-Coulomb and linear elastic models

Properties	Weathered clay	Backfill sand	Weather crust	Medium Stiff clay	Stiff clay	DCM column	Concrete pile
Unit weight, γ (kN/m ³)	16	17	17	18	19	15	24
Elastic modulus, E (kPa)	3000	7500	2500	5000	900	30000	2.8×10^7
Poisson's ratio, ν	0.25	0.3	0.25	0.25	0.25	0.20	0.15
Cohesion, c (kPa)	10	8	10	10	30	200	8000
Friction angle, ϕ (degree)	26	29	23	25	26	30	40

Table 2. Parameters used in soft soil model

Properties	Soft clay
Unit weight, γ (kN/m ³)	15
Modified compression index, λ^*	0.15
Modified swelling index, κ^*	0.03
Poisson's ratio, ν	0.15
Cohesion, c (kPa)	4
Angle of internal friction, ϕ (degree)	23
Overconsolidation ratio (OCR)	1.5

parameters used in this study are listed in Tables 1 and 2 for the Mohr Coulomb and soft soil models, respectively.

Analysis Results

Bending Moment Profile

Figure 6 presents the bending moment profiles of the DCM and SDCM columns located at the toes of the embankment. The maximum values of the bending moments were 3 and 11 kN-m for the DCM and SDCM columns, respectively, which correspond to the factors of safety against the bending moment failure of 1.13 and 1.73, respectively. It can be seen that the SDCM column has a higher potential to prevent bending failure than the DCM column under the embankment. In addition, local failure induced by bending moment may occur in the DCM column under the embankment for this study.

Axial Load

The maximum axial loads obtained from the analysis were 90 and 130 kN, for the DCM and SDCM columns under the crests of the embankment, respectively, which correspond to the factors of safety against the bearing capacity failure of 1.56 and 2.42, respectively. Thus, the factor of safety against the bearing capacity failure for the SDCM column was 1.55 times larger than that for the DCM column.

Slope Stability

The strength reduction method was used to calculate the factors of safety against slope failure. The results show that the embankment built on soft clay improved with the SDCM and DCM columns and provided the factors of safety against slope failure of 1.65 and 1.35, respectively. Thus, the factor of safety against

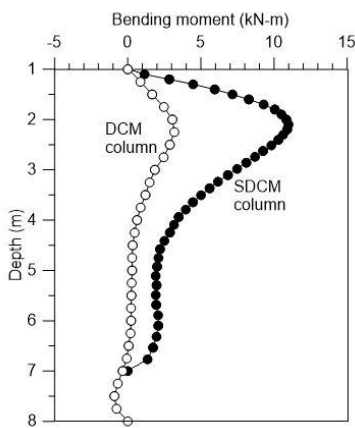


Figure 6. Bending moment profiles of DCM and SDCM column located at the toe of the embankment obtained from three-dimensional finite element analysis

Material Models and Parameters

The Mohr Coulomb model was selected to model the behavior of the backfill soil materials, weathered crust, medium stiff clay and stiff clay, DCM column, and prestressed concrete core pile, whereas the soft soil model was used to model the soft clay layer. The

slope failure for the SDCM column was 1.22 times higher than that for the DCM column.

Conclusions

In this study, axial compression and lateral load tests on the SDCM and DCM columns were conducted, and a field SDCM and DCM column-supported embankment was analyzed using a three-dimensional finite element analysis. From the field test results and the numerical results, the following conclusions can be drawn:

1. The vertical ultimate bearing capacities of the DCM column is significantly lower by as much as 180 kN or 60 % compared to the SDCM column and the lateral ultimate bearing capacity of the SDCM column can be improved by a factor of 13 compared to the DCM column due to the low strength and quality that commonly occurs on a DCM column.

2. For the embankment test, the SDCM column is more effective than the DCM column in terms of reductions of settlement and lateral displacement of soft ground, and increases in bearing capacity, slope stability, and the lateral resistance of the soft clay foundation.

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