

NUMERICAL INVESTIGATION ON LATERAL MOVEMENTS OF A COMPOUND DEEP CEMENT MIXING WALL

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Abstract

This paper presents parameters affecting the lateral movement of a compound deep cement mixing retaining wall using the three-dimensional finite element method. A numerical model is first calibrated with an instrumented case history. Then, a parametric study is performed. The influences of various parameters are compared and rated in terms of the degree of importance. The numerical results show that the thickness of the soft clay, the modulus of elasticity of the deep cement mixing column, and the nonexistence of the stabilized mat are the 3 most important design parameters.

Keywords: Deep mixing, excavation, parametric study, simulation, soil stabilization

Introduction

Sheet pile walls, contiguous pile walls, and diaphragm walls are commonly used as retention systems for deep excavations in soft clays (Wang *et al.*, 2010). Sheet pile walls are among the most commonly used to support deep excavations because of their low operational costs, but larger displacements due to low structural stiffnesses may occur. The use of contiguous pile walls and diaphragm walls comprising thick cast-in-place reinforced

concrete walls in the ground can avert the problems of sheet pile walls, but the costs of such concrete walls are relatively high (Shao *et al.*, 2005). Deep cement mixing (DCM) and stiffened DCM (SDCM) walls, which are alternative retaining structures, have been introduced to support deep excavations in soft clays over the past 20 years in many countries (Jamsawang *et al.*, 2015b). In a DCM wall, the columns are formed by mixing in situ soil with

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cement. A DCM wall will typically have a thick cross-section due to its low tensile strength and is typically excavated without struts. SDCM walls, which are constructed by inserting steel H-beams into DCM columns to increase the bending moment capacity, are an improvement over DCM walls (Jamsawang *et al.*, 2011). Thus, the thickness of a DCM wall can be reduced (Wang *et al.*, 2010). The DCM wall can function either as a temporary support of an excavation or as a permanent retaining wall. Permanent walls have been constructed by adding a concrete facing to the DCM wall, which is called a “compound DCM wall”. The concrete facing acts as a stronger member resisting lateral active force whereas the DCM columns behind the concrete facing stabilize the soft clay properties.

Much research has been conducted using three-dimensional (3-D) finite element analysis to investigate the performances of excavations involving contiguous pile, diaphragm, and SDCM walls in terms of lateral wall movements (Hou *et al.*, 2009; Hsieh *et al.*, 2013; Likitlersuang *et al.*, 2013; Ou *et al.*, 2013; Ignat *et al.*, 2015; Zhang *et al.*, 2015; Hsiung *et al.*, 2016; Lim *et al.*, 2016). However, limited studies on the parameters affecting lateral movements of performance of compound DCM walls have been conducted using field observations and numerical investigations.

In this paper, a parametric study based on 3-D finite element analysis was conducted to investigate the lateral movements of a compound

DCM wall. A full-scale compound DCM wall was constructed on a soft Bangkok clay deposit. The wall was instrumented with an inclinometer to study its lateral behavior after the excavation. The calibration of the finite element method (FEM) model was performed first. A parametric study was then conducted to evaluate the influence of various parameters on the lateral movement of the wall.

Soil Condition and Wall Description

The case history was of a reservoir construction project belonging to the Electricity Generating Authority of Thailand (EGAT) at Wang Noi Power Plant, Thailand. The general soil profile of this project was obtained from 5 boreholes. The uppermost layer is a soft clay subsoil layer underlain by a stiff clay layer. The thicknesses of the soft clay layer varied from 3 to 5 m in an excavated area for the construction of the reservoir. The maximum thickness of the soft clay layer found from a borehole outside the excavated area was 8 m. The undrained shear strengths obtained from the unconfined compressive strengths of the soft clay and stiff clay were 17 and 90 kPa, respectively.

The constructed compound DCM wall was approximately 830-m long, 5.5-m high and 10-m wide. The DCM wall layout is shown in Figure 1. A precast concrete wall was first driven to a depth of -8.0 m and, subsequently, a tangential DCM column wall

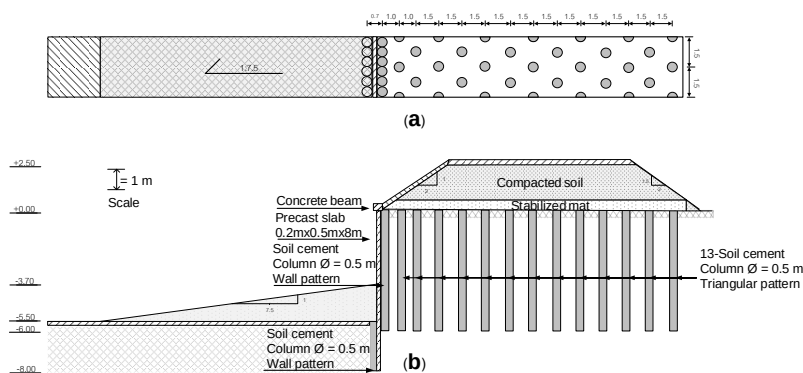


Figure 1. Layout of compound DCM wall: (a) plan view, (b) section view

was constructed behind the precast concrete wall using a deep jet grouting method. The water-cement ratio of the slurry and the cement content were 1.0 and 225 kg/m³ of soil, respectively. Then, the DCM columns under the embankment were installed in a triangular pattern. All the DCM columns had a diameter of 0.5 m and a depth of -6.00 m in the embankment side. A stabilized mat with a thickness of 0.5 m consisting of soil-cement slurry was constructed over the length of the wall. In addition, a 2-m long DCM wall was also constructed near the precast concrete panels at the bottom of the reservoir at the depth of -8.00 m. The excavation was divided into 2 steps. For the first step, the excavation was performed to a level of -3.50 m. Next, excavation with a slope of 1:7.5 from an elevation of -3.50 m in front of the retaining wall to the bottom level of -5.50 m was performed to create a counterweight berm. An inclinometer tube was installed near the wall at a depth of -8 m to monitor lateral wall movements.

Core samples with a total number of 500 specimens were randomly extracted from the DCM columns at various depths over the construction area for use in unconfined compression tests in the laboratory to determine the unconfined compressive strength $q_{u(DCM)}$ and the secant modulus of elasticity corresponding to 50% of the unconfined compressive strength E_{DCM} . The values of the unconfined compressive strength ranged from

0.6 to 5 MPa, with an average value of 0.8 kPa, while the modulus of elasticity ranged from 20 to 750 MPa, with an average value of 250 MPa.

Numerical Analysis of the Field Case Study

Finite-Element Mesh and Boundary Condition

A finite element simulation was performed to assist in understanding the compound DCM wall behavior using the PLAXIS 3D Foundation software version 2.2. The 3-D finite element model consisted of the DCM columns, embankment, stabilized mat, foundation soils, and precast concrete wall. Figure 2 illustrates the 3-D finite element mesh that was used in the back-analysis, which corresponds to the compound DCM column wall configuration in Figure 1. The 3-D mesh was 1.5-m wide, 55-m long, and 20-m deep. For the boundary condition, horizontal displacements were prevented, and vertical displacements were free to occur at the side boundaries. Both horizontal and vertical displacements were prevented from occurring at the bottom boundary.

Constitutive Model and Model Parameters

The DCM columns, the stabilized mat, and the embankment were modeled as linearly elastic to perfectly plastic materials with the

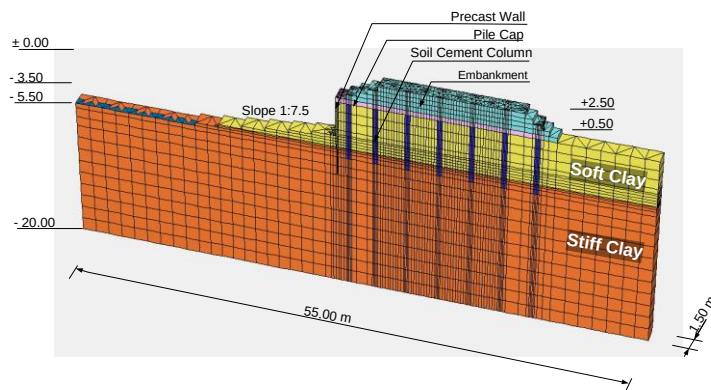


Figure 2. Typical finite-element mesh used in this study

Mohr-Coulomb model (Mun *et al.*, 2012; Jamsawang *et al.*, 2015a, 2015b, 2016a, 2016b). The precast concrete wall was modeled as structural elements using a linear elastic model. The Hardening soil model, which is an advanced soil model (Jamsawang *et al.*, 2015a, 2015b, 2016a, 2016b), was used to model the behavior of the soft clay and the stiff clay in this study. The parameters of the foundation soils and wall used for the 3-D FEM for this study are presented in Tables 1 and 2.

Model Calibration using Field Observations

Figure 3 presents a measured lateral movement profile of the compound DCM column wall after completion of the excavation. The maximum lateral movement was found to be 40 mm at a depth of 1 m below the surface. Due to the variations in the elastic modulus

values of the DCM columns, the calibration of the field observation results was performed using 3-D FEM models, as shown in Figure 2, to obtain the reasonable elastic modulus for simulation of the behavior of the DCM columns. For the calibration of the model, the parameters for the soft clay, stiff clay, embankment, stabilized mat, precast wall, and DCM columns are illustrated in Tables 1 and 2. The moduli of the DCM columns (E_{DCM}) were varied so that the measured lateral movement profile could be matched by the calculated lateral movements. The back-calculated value for E_{DCM} was 40 MPa, which gives the best fit of the lateral movement profile. The lateral movement profile calculated by 3-D FEM using an E_{DCM} of 40 MPa is the so-called “case history” used as a “base problem” for the parametric study in the following Sections.

Table 1. Parameters used in hardening soil model

	Soft clay	Stiff clay
Unit weight, γ (kN/m ³)	15	18
Secant stiffness, E_{50}^{ref} (kPa)	1,000	9,000
Tangential stiffness, E_{oed}^{ref} (kPa)	1,000	9,000
Unloading and reloading stiffness, E_{ur}^{ref} (kPa)	6,500	120,000
Power of the stress-level dependency of the stiffness, m	0.8	0.4
Poisson's ratio for unloading-reloading, ν_{ur}	0.2	0.2
Effective cohesion, c' (kPa)	2	30
Effective friction angle, ϕ' (degree)	22	26
Angle of dilatancy, ψ (degree)	0	0
Over-consolidation ratio, OCR	1.5	8
Material behavior	Undrained	Undrained

Table 2. Parameters used in Mohr-Coulomb and linear elastic models

	Embankment	Stabilized mat	DCM column	Precast wall
Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	linear elastic
Unit weight, γ (kN/m ³)	20	15	15	24
Elastic modulus, E (kPa)	20,000	250,000	40,000	2.6×10^7
Poisson's ratio, ν	0.33	0.25	0.33	0.15
Cohesion, c (kPa)	10	900	400	-
Friction angle, ϕ (degree)	30	0	0	-
Tensile strength, σ_t (kPa)	-	144	64	-
Material behavior	Drained	Undrained	Undrained	-

Parametric Analyses

It is clear that the case history analysis can be improved significantly by varying a number of parameters affecting the lateral movement of the compound DCM wall after construction. The parameters analyzed are: (1) the nonexistence of the stabilized mat, (2) the nonexistence of the front DCM wall, (3) the pattern of the DCM column, (4) the modulus of elasticity of the DCM column, (5) the modulus of elasticity of the stabilized mat, (6) the size of the DCM column, (7) the length of the DCM column, and (8) the thickness of the soft clay. As mentioned previously, 1 parameter was varied from the case history during each analysis to determine the influence of that specific parameter.

Effect of the Nonexistence of Stabilized Mat

In the case of the excavation work, the stabilized mat acts as a rigid platform that ties individual columns together and acting as a column group that effectively resists lateral forces and movements, and also acting as a relieving platform for surface loads due to construction traffic and material. The effect of the nonexistence of a stabilized mat was simulated by omitting the stabilized mat from the top of the DCM columns. As shown in

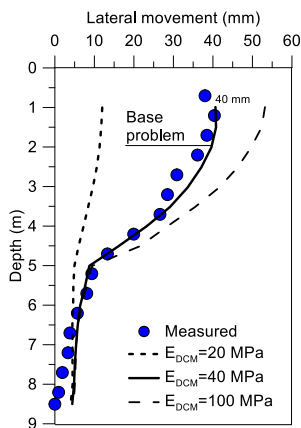


Figure 3. Measured versus predicted wall lateral movements

Figure 4, the DCM wall simulation without the stabilized mat resulted in much larger lateral movements. The maximum lateral movement was 98 mm higher and approximately twice the maximum lateral movement than in the case of the DCM wall simulation with a stabilized mat, due to the nonexistence of the stabilized mat to tie them together.

Effect of the Nonexistence of Front DCM Column Wall

In the case history, the DCM column wall in front of the precast wall was installed to increase passive resistance, resulting in limiting lateral movement. The influence of the existence of the front column wall was investigated by removing it from the model. The results show (Figure 4) that the nonexistence of the front column wall has a small influence on the lateral movement (maximum lateral movement = 47 mm). This reveals that the compound DCM wall without the front column wall exhibited a completely passive resistance to limit the lateral movement. Thus, the front column wall is useless in this wall system.

Effect of the DCM Column Pattern

The pattern of the DCM column behind the wall of the case history is a triangular

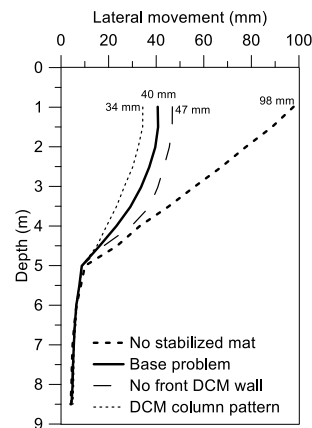


Figure 4. Effects of stabilized mat, nonexistence of front DCM wall, and DCM column pattern

pattern. The column row pattern has been used to increase the rigidity of the DCM wall against horizontal sliding forces (Larsson *et al.*, 2012). Thus, the effect of the DCM column pattern on lateral movement of the compound DCM wall was investigated by changing geometries from a triangular pattern to a column row pattern with the same number of the DCM columns. The results in Figure 4 present that the column row pattern slightly affects the lateral movement (maximum lateral movement = 34 mm). This implies that the compound DCM wall with a triangular pattern has sufficient rigidity to resist the lateral movement.

Effect of the Modulus of Elasticity of DCM Column

To evaluate the influence of non-uniformity of mixing soil and cement, 6 values of E_{DCM} were considered: 20, 40, 100, 250, 500, and 750 MPa, which cover the variation ranges of the test results. The values of 20, 250, and 750 MPa correspond to the minimum, mean, and maximum moduli found in the test results of this study. The effect of E_{DCM} on the maximum lateral movements is presented in Figure 5. The figure shows that the column modulus has a substantial effect on the maximum lateral movements. As expected, the results show that the overall tendency is the reduction in lateral movements with increasing stiffness of the column. The values of the maximum lateral movement calculated using the minimum, mean, and maximum E_{DCM} were

53, 21, and 13 mm, respectively. It can be observed that use of the mean value of E_{DCM} in designing the compound DCM wall underestimates the true value because the lateral movement is approximately 2 times higher than that from the case history (40 mm). The use of the minimum E_{DCM} is more conservative. If all DCM columns have high degrees of homogeneity with very high-quality control (the maximum E_{DCM} can be obtained), the maximum lateral movement can be minimized by as much as 13 mm using DCM columns in this project.

Effect of the Modulus of Elasticity of Stabilized Mat

To evaluate the influence of the stiffness of the stabilized mat, 3 values of modulus of elasticity were considered: 20, 250, and 1,000 MPa, which cover the variation ranges of test results and correspond to the minimum, mean, and maximum moduli. Figure 6 shows that for the increasing modulus, the lateral displacements decrease as expected. The modulus significantly reduces the lateral movements as the modulus increases from 20 to 40 MPa. The influence of the modulus is not obvious when the modulus exceeds 40 MPa. Moreover, the reduction in lateral movements is virtually constant for a modulus greater than 100 MPa. Thus, an increase in the modulus of elasticity of the stabilized mat can decrease the maximum lateral movement by as much as 34 mm.

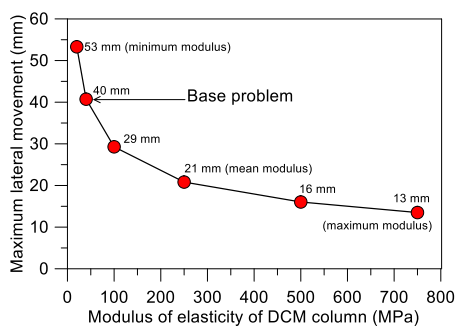


Figure 5. Effect of modulus of elasticity of DCM column

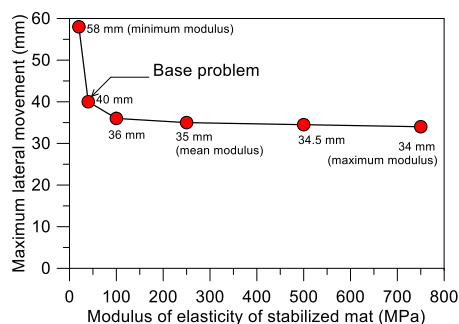


Figure 6. Effect of modulus of elasticity of stabilized mat

Effect of the Size of DCM Column

To limit the lateral movement of the compound DCM wall, the size of the DCM column, by increasing the diameter of the columns, is introduced in this paper. Increasing the column size results in a larger soil improvement zone. Thus, the global stiffness of the soil behind the precast wall increases, resulting in reduced lateral movement. The diameter of the DCM column was increased to 1 m (keeping the column spacing constant) compared to the diameter of 0.5 m used in the case history. The result shows the reduced lateral movement, as shown in Figure 7. Based on the simulation result, it was found that the size of the DCM column has negligible influence on the overall lateral movement.

Effect of the Embedment of DCM Column

In this study, the embedment is defined as the length of the DCM column that is embedded in the stiff clay layer. The aim of increasing the embedment is to obtain a fixity condition of the DCM column. The lateral movement can be minimized when the fixity condition is reached (Kourkoulis *et al.*, 2011). The embedment of the DCM column was increased to 4 m compared to the embedment of 1 m in the case history. Figure 8 shows that the lateral movement does not affect the lateral movement of the wall. Thus, it is unnecessary to increase the embedment in the stiff clay layer; however, the tips of the DCM columns should be placed on top of the stiff clay layer

to prevent the soft clay moving under the tips of the DCM columns.

Effect of Thickness of Soft Clay Layer

Variations in the soil profile are a major problem in geotechnical engineering. Subsurface investigations are needed to be performed over the whole construction area to obtain sufficient soil data. An insufficient number of boreholes can cause underestimations in the design process. To evaluate the influence of the soft clay layer, 6 values of the soft clay layer were considered: 3, 4, 5, 6, 7, and 8 m which cover the variation of ranges of soil data obtained from the subsurface investigations.

Figure 9 shows that for increasing the soft clay thickness, the lateral displacements increase, as expected. The thicker soft clay layer produces larger active lateral forces acting on the precast wall, causing larger

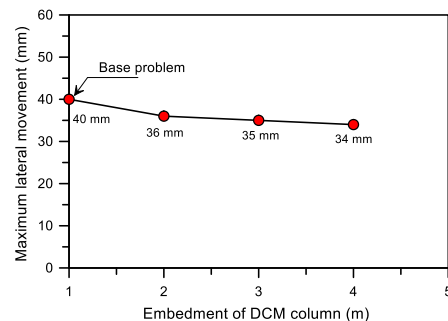


Figure 8. Effect embedment of the DCM column

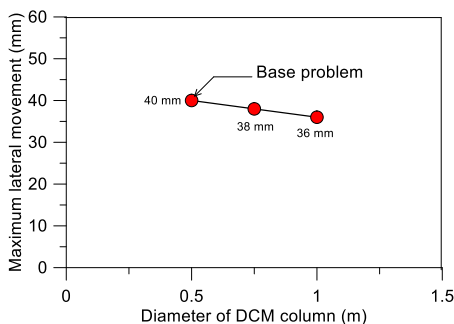


Figure 7. Effect of size of DCM column

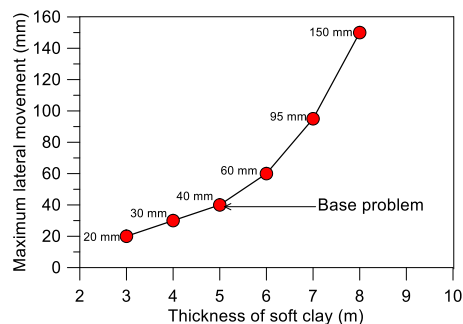


Figure 9. Effect of thickness of soft clay

lateral movements. This is similar to an excavation in soft clay. Nevertheless, the thinner soft clay layer produces smaller active lateral forces, which is similar to an excavation in stiff clay. The thickness of the soft clay layer significantly increases the lateral movements as the soft clay thickness increases from 7 to 8 m. The maximum lateral movements range from 20 to 150 mm when the soft clay thickness varies between 3 and 8 m, respectively.

Discussion

The influences of various factors on the lateral movements are presented above and are summarized and rated below. The degree of influence of each influential factor on the maximum lateral movements was defined as the ratio of the variation in the maximum lateral movements to the mean of the maximum lateral movements (Huang and Han, 2010). For example, the maximum lateral movement for E_{DCM} of 20, 40, 100, 250, 500, and 750 MPa were 53, 40, 29, 21, 16, and 13 mm, respectively.

The variation in the maximum lateral movement within the E_{DCM} range investigated was $|53-13| = 40$ mm, and the mean of the maximum lateral movement was $(53+13)/2 = 33$ mm. Consequently, the degree of influence of E_{DCM} on the maximum lateral movement was calculated to be $40/33 \times 100\% = 121\%$. The calculated degree of influence for each factor is listed in Table 3. The degree of influence on the lateral movement was divided into 5 levels:

extreme, very high, high, medium, and low. Because there was no standard to define these levels, the common concept of significance in geotechnical engineering was adopted (Huang and Han, 2010). The degrees of influence less than 30%, between 30 and 60%, between 60 and 100%, between 100 and 130%, and greater than 130 were considered to be low, medium, high, very high, and extreme, respectively. Table 3 also shows the ranks of all factors based on the degree of influence (%). It can be observed that only the modulus of elasticity of the stabilized mat has medium influence, whereas the nonexistence of the stabilized mat, the modulus of elasticity of the DCM column, and the thickness of the soft clay layer have high to extreme influences on the lateral movements of the compound DCM wall; therefore, they can be considered as the 3 most important design parameters. However, the embedment of the DCM column, DCM column pattern, nonexistence of front DCM wall, and size of DCM column have a low effect; thus, they are unimportant design parameters.

Conclusions

A case history of a compound DCM wall used in deep excavation for a reservoir construction project in soft Bangkok clay was reported. The lateral movement of this wall during construction was observed. The calibration of field observation results was performed to obtain the elastic modulus of the DCM columns. Then, a study on the parameters

Table 3. Rank of degree of influence on maximum lateral movement

Rank	Factors	Degree of influence	
		(%)	Class
1	Thickness of soft clay layer	153	Extreme
2	Modulus of elasticity of DCM column	121	Very high
3	Nonexistence of stabilized mat	84	High
4	Modulus of elasticity of stabilized mat	54	Medium
5	Embedment of DCM column	16	Low
5	DCM column pattern	16	Low
5	Nonexistence of front DCM wall	16	Low
6	Size of DCM column	11	Low

affecting the lateral movement was performed to analyze the degree of influence of different parameters on the maximum lateral movement of the compound DCM wall. The conclusions can be drawn from the analysis results that the stabilized mat, the modulus of elasticity of the DCM column, and the thickness of the soft clay layer are the 3 most important design parameters for minimizing the lateral movements of the CDCM wall. The thickness of the soft clay layer seems to be the most important factor. Increasing the thickness of the soft clay resulted in larger lateral soil movement. However, the embedment of the DCM column, the DCM column pattern, the front DCM wall, and size of DCM column are insignificant design parameters.

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