Evaluation of key design features for embankment constructed with deep cement mixing piles on soft clay

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Abstract

The constructions of high canal embankments on soft clays are faced with an enormous challenge in slope stability due to the instability of soft clay foundation and excessive lateral movement of soil if supported only by deep cement mixing (DCM) piles. A canal embankment supported by concrete piles with slab and DCM piles along the slope is currently being constructed on Bangkok soft clay in Bangkok, Thailand. In this paper, a numerical parametric study was performed using a finite element program to determine key design features that could affect the stability and lateral movement of the embankment. Differential settlement of the embankment in long-term conditions was also analyzed. The soil parameters used in the numerical analysis were back-calibrated using field measurement data obtained from a prior DCM pile project constructed on similar Bangkok soft clay in Bangkok, Thailand. It was concluded that the following four parametric characteristics including (1) the feasibility of concrete piles with slabs instead of the sole use of DCM piles, (2) the water level in the newly excavated canal, (3) the pattern of DCM piles, and (4) the length of the piles are considered as the critical design features that could significantly affect the stability and lateral movement of the embankment.

Keywords: Slope stability, Lateral movement, Differential settlement, Concrete pile with slab, DCM pile.

1. Introduction

Soft clay is a geological material representing a prominent category of problematic soils and is commonly found in coastal areas as sedimentary layers. Improving the strength and stiffness of the Bangkok soft clay using the deep mixing method (DCM) is a well-established practice in Thailand. However, high embankment loads, changes in the groundwater table, and canal construction stage along with a variety of other natural factors could cause the slopes to be damaged if supported only by DCM piles. The parametric studies of some canal digging projects in Thailand show that the combined effect of the geometric parameters on the excavation performance and slope stability are different and complex. For this reason, it is essential to monitor the actual behavior of the soft ground after excavation and embankment construction works by instruments. The field and laboratory collected data are used to improve the accuracy of FEM analysis by reviewing the parameters regarding the LM of the excavated slope and differential settlement. Because of this complicacy, FEM using the PLAXIS software is the essential factor in perceiving the effect of the parameters of stabilized slopes due to lateral load and the differential settlement. Consequently, an accurate analysis not only will provide stability to the slope of the embankment but also will give practical guidance for the future design of similar kinds of projects.

2. Soil Profile and Index Properties

The soil profile and index properties of the subsoils at the project site are in Figure 1. The undrained shear strength (S_u) from soft clay to stiff clay was determined from field vane shear (FVS) and unconfined compression tests; the topmost weathered crust layer showed the S_u at about 16.5 to 33.2 kN/m^2 and less compressibility at about 3 m depth owing to the chemical & physical weathering process, compaction, and desiccation. After that, the soft clay layer started with a low S_u value, and the S_u increased slightly with depth, from 12.0 kN/m^2 to 26.5 kN/m^2. The soil physical characteristics in the survey area were also comparable to those of the Bangkok soil.

The undrained shear strength is crucial when determining short-term stability and bearing capacity. The ICU test was performed to assess the undrained shear strength in the laboratory. Strain softening was observed after the deviator stress had reached its peak. Throughout the ICU test, the excess PWP was raised by a positive value with the strain. No sharp peaks were observed in the excess PWP-strain relationship. Table 1 shows the comparison of $E_{u,50}$ from 4 boreholes data. Typically, the low water content results in a high modulus of elasticity in the soil.

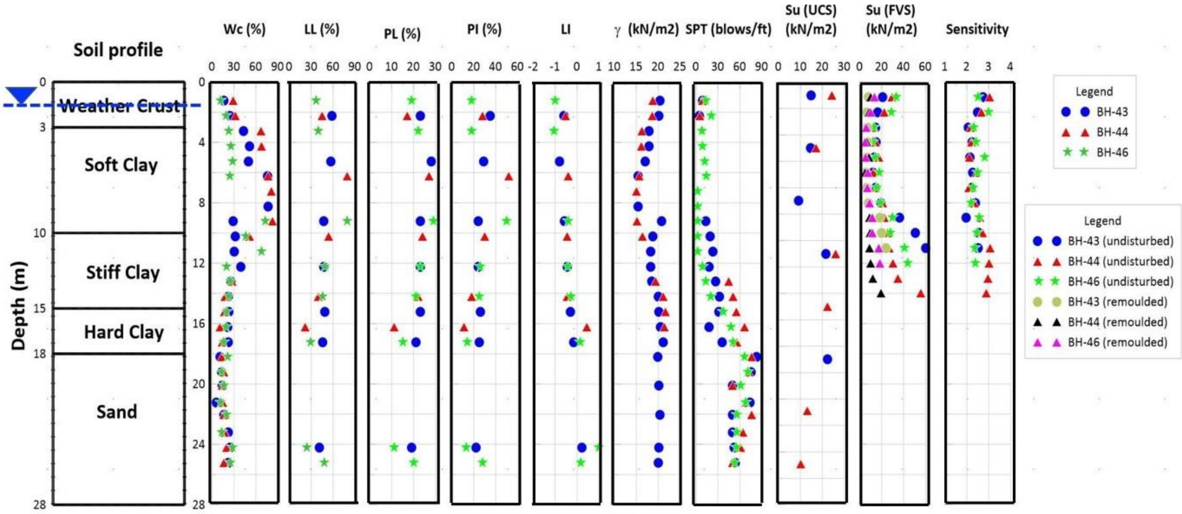

Figure 1: Soil profile and index properties of the subsoils at the project site.

$E_{u,50}$ (t/m²)	BH-16 (2.0 m - 3.5 m)	BH-38 (3.0 m - 4.5 m)	BH-21 (5.0 m - 6.5 m)	BH-32 (6.0 m -7.5 m)
$E_{u,50}$ at σ_c=22.5 (t/m²)	-	163.34	320.16	295.60
$E_{u,50}$ at σ_c=25.0 (t/m²)	305.01	258.10	307.26	298.08
$E_{u,50}$ at σ_c=30.0 (t/m²)	338.72	321.14	283.77	382.19
$E_{u,50}$ at σ_c=35.0 (t/m²)	254.50	453.15	195.78	279.78

Table 1: Summary of $E_{u,50}$ between 4 boreholes at different depths.

3. Numerical Modeling Analyses

3.1 Soil Parameter Back Analysis

To ensure the reliability of the proposed model of the concerned project with confidence, a numerical back analysis of the Suvarnabhumi Drainage Canal Project, which had slopes stabilized with DCM piles on Bangkok soft clay, was conducted to calibrate the soil parameters using field monitoring data. The $E_{u,50}$ values of the Suvarnabhumi Drainage Canal Project were estimated in the study. The $E_{u,50}$ data from laboratory tests and the data numerically derived from the Suvarnabhumi Drainage Canal Project were also substantiated by the existing literature on Bangkok soft clay.

Figure 2 shows the cross-section with the initial design in section-I of the Suvarnabhumi Drainage Canal Project. PLAXIS 2D finite element software was used in the study. The total stress analysis was used to correspond with the rapid rate of construction. The simulation was performed based on the following construction stages: Stage 0: generation of the initial stresses (K_0 - condition), Stage 1: installation of the DCM piles, Stage 2: installation of roadway, Stage 3: excavation of 3.0 m slope, and Stage 4: excavation of 3.0 m slopes. The equivalent area (EA) method (Ariyarathne et al. 2013) for a square column arrangement and the equivalent properties (EP) approach for the panels or tangential piles were adopted (Poon and Chan 2012; Huang et al. 2009) in this analysis. Table 2 lists the parameters used in the Mohr-Column (MC) model for the back analysis.

Figure 3 shows the lateral movement (LM) and settlement values obtained from the model and the field monitoring. As shown in Figure 3, the LM and settlement analyzed from the MC model were 94 cm and 59 cm, respectively, which were very close to the actual field measured data (LM and settlement were about 1.0 m and 60 cm, respectively). From the back analysis of the FEM results, the α value was 150 for soft clay of the Suvarnabhumi canal project. On the other hand, the α value was 136 to 178 for soft clay of this project which was collected from the ICU triaxial compression test. The empirical correlation was well supported by the α value of 150 suggested by Berdado (1990), Futaki et al. (1996), and Asano et al. (1996). Finally, $E_u = 150S_u$ was used for the analysis in the study.

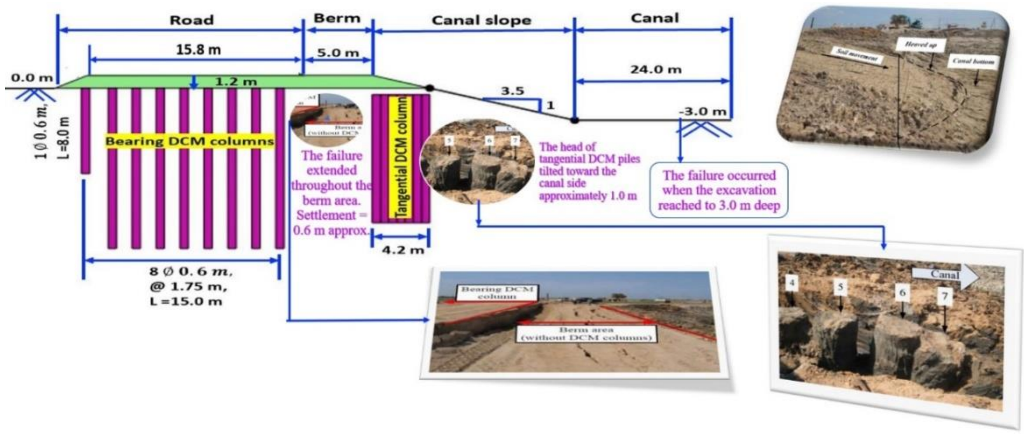

Figure 2: Cross-section with initial design at section-I for back analysis (Phermphorn Buathong, 2014).

Parameter	Very soft clay	Soft clay	Medium Stiff clay	Stiff clay	DCM pile	Embankment (Roadway)
Depth (m)	0.00 – 5.5	5.50 – 15.00	15.00 -19.20	19.20 – 20.80		
Model	MC	MC	MC	MC	MC	MC
$E_u (kN/m^2)$	75 - 200S_u	100 - 200S_u	300S_u	600S_u	225000	7500
$\gamma (kN/m^3)$	15.50	15.50	17.00	18.00	15.00	20
ϑ_u	0.495	0.495	0.495	0.495	0.33	0.33
$\phi^{(o)}$	-	-	-	-	-	29
$S_u (kN/m^2)$	5	7	27	132.5	500	C'=8
S_u increment (kPa/m)	0.21	1.8	7.86	0	0	0

Table 2: List of MC model parameters for back-analysis.

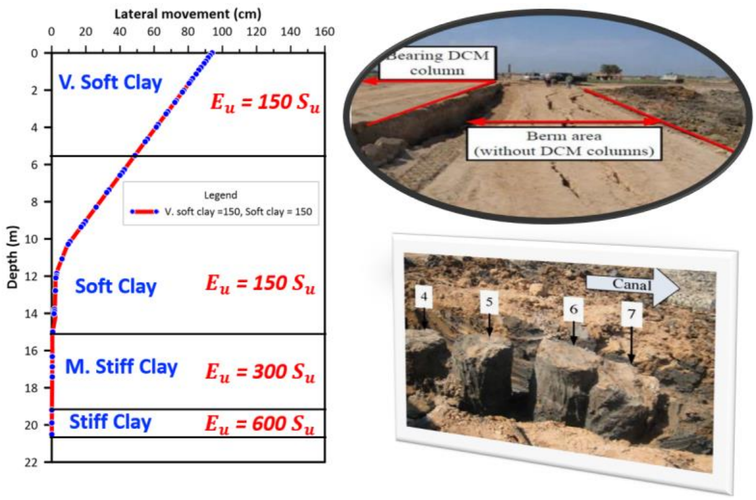

Figure 3: Comparison of LM and settlement between the field measurement and FEM results.

3.2 Construction Stages of the Project

A total stress analysis was conducted for the stability of the embankment and canal slope under short-term conditions, whereas an effective stress analysis was conducted for the model under long-term conditions. Figure 4 shows the cross-section and the DCM pile locations for the project. Table 3 describes the soil parameters used in the construction stage modeling.

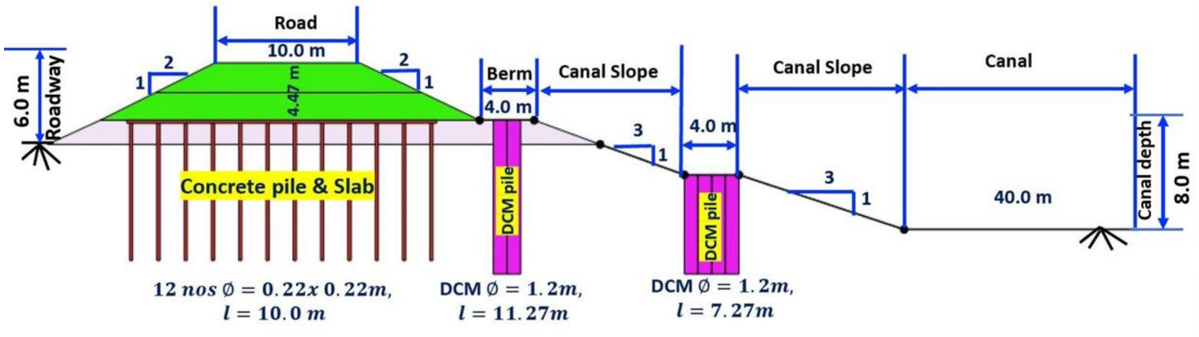

Figure 4: Cross-section and DCM pile locations for the project.

Parameter	Weather Crust	Soft clay	Stiff clay	Hard clay	Sand	DCM Pile	Concrete pile & slab	Embankment (Roadway)
Depth (m)	0.0-3.0	3.0-10.0	10.0-15.0	15.0-18.0	18.0-26.0			
Model	MC	MC	MC	MC	MC	MC	MC	MC
$E_u\ (kN/m^2)$	300Su	150Su	600Su	600Su	-	-	-	-
v'	0.33	0.33	0.33	0.33	0.33	0.33	0.2	0.33
$E'(kN/m^2)$	6650	1596	14630	117040	50000	199500	23500000	50000
$\gamma\ (kN/m^3)$	19.5	16.5	19.5	20.85	20	15	24	20
$\phi^{(o)}$	-	-	-	-	45	-	-	45
$S_u\ (kN/m^2)$	25.0	12.0	27.5	220	C'=0	500	-	C'=0
S_u increment (kPa/m)	0	2.3	8.5	0	0	0		

Table 3: Parameters used in the construction stage modelling

The actual construction stages for the project are as follows: Stage 0: generation of the initial stresses, Stage 1: installation of the concrete piles and slab, Stages 2-10: excavation from 0.5 m to 8 m at an 0.5 m interval, Stage 11: construction of embankment up to 3 m, and Stage 12: construction of embankment up to 6 m. The slope of the excavated slope was 1V:3H. This study was focused on the amount of deferential settlement when the primary consolidation was completed and confirmed the necessity of countermeasures. The factor of safety (FS) were 1.2 and 1.5 during the construction and service period, respectively, for the project. According to the case study findings, when the embankment construction was started after the canal excavation, the LM increased from approximately 66 mm to 80 mm. A high embankment accelerated the slope's lateral movement tremendously.

Figure 5 shows the failure (max. LM) that occurs locally in the soft clay layer zone at the slope of the canal and lateral movement profile at location I_1. According to O'Rourke and Clough (1990), the maximum average LM of walls in stiff clays, residual soils, and sands is 0.2 percent of the total excavation depth, though it can reach 0.5% or more in some situations. CDCM walls with embankment, and without embankment, the ratios were found to be 0.85 % and 0.3 %, respectively. Figure 5 indicates that the predicted maximum lateral movement is around 80 mm at the end of the construction period in the project. According to O'Rourke and Clough (1990) and Hsieh et al. (2013), the ratio is 80mm/8m = 1%, which is 0.35% larger than the maximum allowable lateral movement.

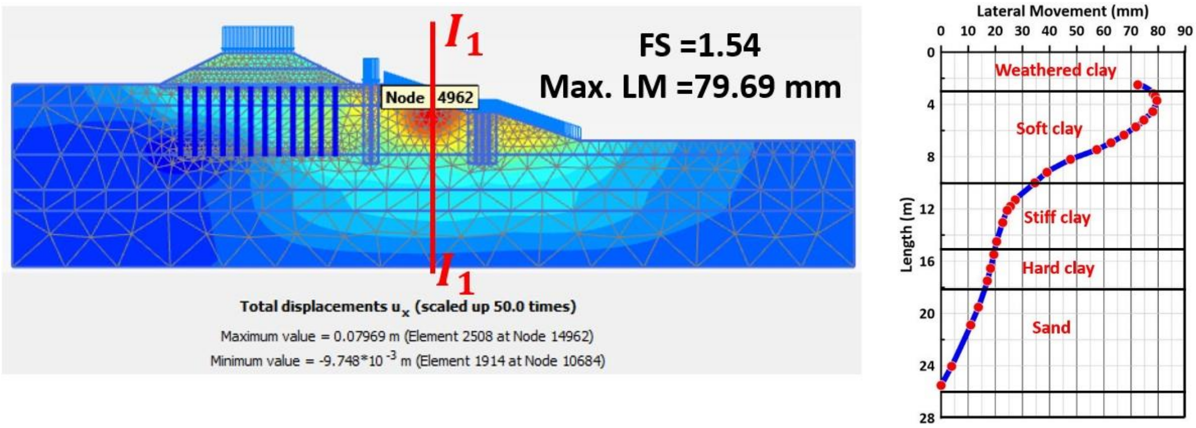

Figure 5: Simulation results of LM and FS.

3.3 Parametric Analyses and Results

Parametric analyses were performed to study the influence of various parameters on the soil's LM to minimize the LM and differential settlement for the embankment. The parameters that were considered in the analyses are discussed in the following sections.

3.3.1 Effect of the Concrete Pile and Slab

In the case of embankment construction along the canal, the concrete slab served as a rigid base that connected every pile, enabling them to work together as a unit to withstand LM, as well as an unloading platform for surface loads. Without the slab, the DCM piles could not resist the high embankment load and cause deformation due to the bending failure and separation of the DCM piles. Figure 6 presents the LM vs. depth and LM vs. FS profiles for the scenarios with and without the slab. As shown in Figure 6, modeling the DCM piles without a slab resulted in an LM of 126.4 mm, which is approximately 2.0 times the maximum lateral movement (79.69 mm) observed when simulating the concrete piles with the slab. The effect of the concrete pile with slab on FS was also presented in Figure 6. When concrete piles with a slab were provided instead of a DCM pile without a slab, there was a substantial rise in FS, which was linked to a significant reduction in lateral movement.

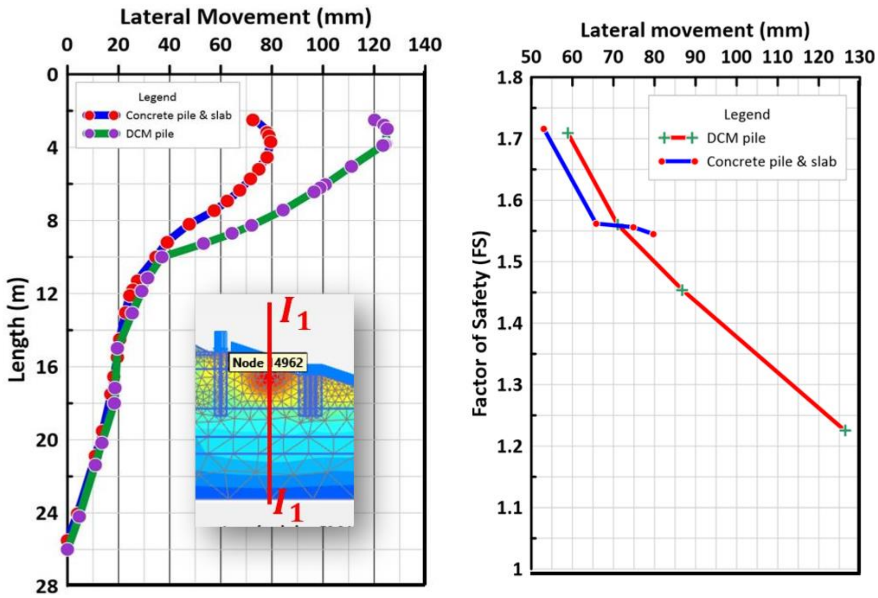

Figure 6: LM vs. depth and LM vs. FS profiles for the scenarios with and without slab.

3.3.2 Impact of Water Level During the Embankment Construction

The drawdown condition is a classical scenario in slope stability. However, during the excavation of a deep canal, the water level must be progressively reduced, which results in further lateral movements. Lowering the water level has two effects: lowering the stabilized external hydrostatic pressure and changing the internal pore water pressure. To prevent slope failure due to lateral movement in rapid drawdown conditions and to study the impact of pouring water, the excavated canal was filled with water at GWL before beginning the embankment construction. The effect of the water level changes on the LM and FS is shown in Figure 7. Figure 7 indicates that if water was poured before the beginning of the embankment construction, it would drastically reduce the lateral movement from 80 mm to 55 mm, and dramatically increase the FS from 1.54 to 1.86 because filled water gave passive resistance against the lateral failure.

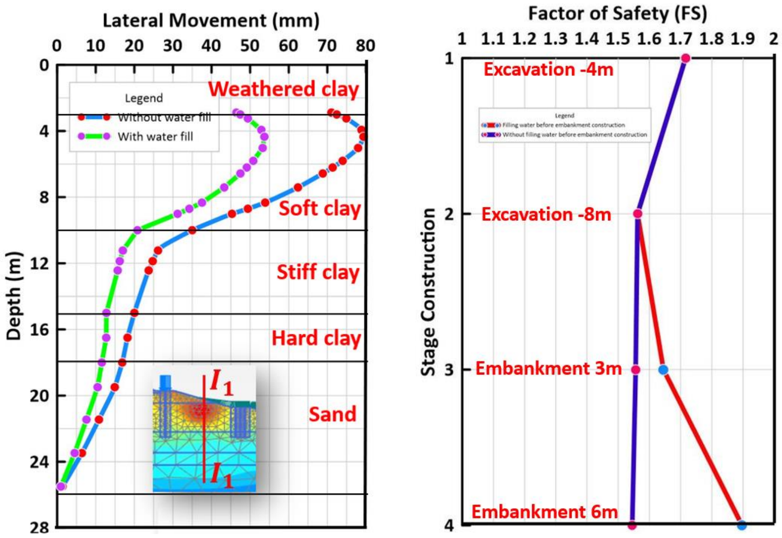

Figure 7: Effect of water level on LM and FS.

3.3.3 The Shape of the DCM Piles

Two conclusions were drawn from the accidents at the Suvarnabhumi drainage canal project. The first one was not to use floating piles in soft clay layers to minimize uneven settlement. The second one was not to use a wall shape pattern of the DCM piles perpendicular to the canal direction because it could cause the soft soil to slip (flow) between the soil-cement columns. In this project, the DCM pile with a block shape pattern was used in a parallel direction to the canal to stop the soil movement towards the canal.

3.3.4 Effect of Differential Settlement on the Embankment Stability

Martin and Hsi (2005) suggested the following suitable limits for differential settlements: the maximum angular distortion is 1% transversely and 0.3% longitudinally in 20 years. Long and O'Riordan (2001) recommended that differential settlement after the operation should not exceed 50 mm within a 25-year design life. Larisch, et al. (2005) suggested that changes in slope gradient due to differential settlement of the embankment in both the longitudinal and transverse directions should be limited to 0.3% to 0.5%. The FEM depicts the maximum differential settlement at the pile tip because of the maximum stress concentration, and the predicted angular distortion below the embankment was 0.42% (= 0.54 / (28-15)) in the transverse direction which was within the acceptable limits according to Hsi and Martin (2005) and Larisch, et al. (2005). Nevertheless, the value of around 54 mm of the predicted maximum differential settlement exceeded the value of 50 mm, according to Long and O'Riordan (2001). Therefore, parametric analysis was performed to minimize the differential settlement. The differential settlement was examined at the embedded length, L, of 9 m, 10 m, 11 m, 12 m, and 13 m. Figure 8 shows the floating behavior of the short-embedded length of the concrete pile when L = 9 m and 10 m. When the embedded length was shorter (L = 9 or 10 m), it did not penetrate to the stable surface, resulting in a more significant differential settlement. Once the length reached 11 m, the settlement tended to reduce significantly. As shown in Figure 8, increasing L would not further reduce differential settlement or increase slope stability after the length reached 11 m.

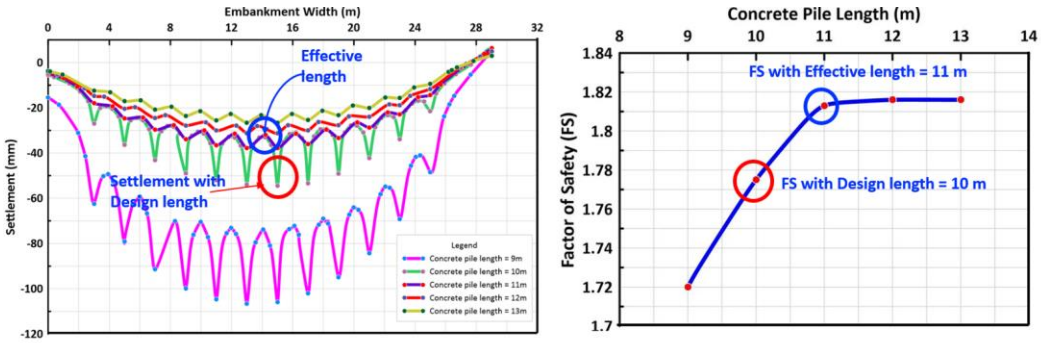

Figure 8: Pile length impact on differential settlement and FS.

4. Conclusions

The following key conclusions were drawn based on the results of the numerical modeling and our experience:

a) This study indicates that the combination of the concrete pile with slab and DCM block shape is very useful for canal embankment construction on the soft clay foundation. The concrete pile with a slab under the embankment could reduce the lateral movement and increase the factor of safety significantly.

b) A wall shape pattern of the DCM piles perpendicular to the canal direction could cause the soft soil to slip between the DCM piles. On the other hand, the DCM pile with a block shape pattern in the parallel direction to the canal could reduce the lateral movement and increase slope stability.

c) The floating piles in soft clay layers couldn't minimize the impact of settlement/differential settlement. A considerable embedded length was required to provide a fixity condition to the stable layer so that the lowest differential settlement was obtained. The results of the analysis indicate that once the length reached 11 m, the settlement tended to reduce significantly to about 16 mm. It was determined that the embedded length of 11 m was an optimum length for the project.

d) The results of our parametric analyses indicate that the following four parametric characteristics including (1) the feasibility of concrete piles with slabs instead of the sole use of DCM piles, (2) the water level in the newly excavated canal, (3) the pattern of DCM piles, and (4) the length of the piles are considered as the critical design features that could significantly affect the stability and lateral movement of the embankment.

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