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Numerical Study on the Settlement of Soft Soil Reinforced by Soil-Cement Columns comparing to Viet Nam standard - A Case Study in Can Tho, Vietnam

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ABSTRACT
Soft clay in the Mekong Delta often settles too much under road embankments. This paper studies how the main geometric factors of soil–cement columns (SCCs)—column length and spacing—change the settlement. Forty-two 2D PLAXIS models were run for four lengths (8, 10, 12, 14 m) and nine spacing ratios (Sc/D = 2.0–4.0, column diameter 0.8 m). For the block ground reinforced by SCC, the calculated settlements were compared with Vietnamese standards TCVN 9403:2012 values and TCCS 41:2022. The results show three clear trends. First, short columns (8 m) give large settlement that grows quickly as spacing widens, while columns 12 m or longer make settlements almost constant for the same spacing range. Second, an economical spacing ratio of Sc/D is from 2.0 to 2.5. Third, the code method is inconsistent: it underestimates settlement for tight grids but overestimates it for long columns with wide grids. The study concludes that 12 m SCCs spaced at 2.0D –3.0D give deltaic clay the best balance between cost and performance. Wider grids or deeper columns should be checked with finite-element analysis to avoid unsafe or overly conservative designs.

1. Introduction

The construction of high road embankments on soft soil has become increasingly common, particularly in Can Tho City and the Mekong Delta region of Vietnam. However, this practice poses significant challenges in terms of cost and stability. Various soil improvement techniques have been widely applied to address these challenges, including sand cushions, sand piles, prefabricated vertical drains (PVD), bamboo piles, wooden piles, and soil-cement piles (CDM). Among these, CDM has gained popularity due to its high efficiency in reinforcing soft soil. This study focuses on simulating the CDM method using finite element modelling to analyse the influence of key factors, such as pile length, distance, diameter, and embankment height, thereby proposing solutions suitable for local conditions.

Soil-cement columns are commonly used due to their pile-like shape. However, according to the Vietnamese standard of TCVN 9403:2012 [1], the official term is “cement column,” as their strength is significantly lower than that of concrete piles. When designing subgrades reinforced with cement columns, they are considered equivalent to a foundation and are applied to projects requiring large-area load-bearing capacity. An advanced ground improvement method involving in-situ deep stabilisation has been implemented to enhance the properties of soft soils using binders such as cement or lime. In particular, cement is commonly injected and blended with the soil using specialised machinery, a process widely known as Deep Cement Mixing (DCM). [2]. This technique has been effectively employed in the construction of embankments [3-5].

In the 1960s–early 1970s, ground-improvement efforts for light buildings and roadway embankments on soft clays focused on limiting total and differential settlement. Field experience showed that in-situ soil-cement columns (SCCs)—0.4 – 0.8 m in diameter and 6 – 10 m deep—could boost bearing capacity and control post-construction deformation, allowing two-storey structures or ~1.5 m embankment fills on normally consolidated clays. Designers accepted overall settlements of roughly 0.2 – 0.3 m for low-rise buildings (larger for embankments) as long as differential movement was minor, and they estimated the clay layer’s settlement by the simple 2:1 stress-distribution method, assuming vertical transfer of the embankment load with negligible lateral spread beneath the reinforced block [6]. Further studies showed that cement-reinforced clay around piles reduces bending moments and increases lateral load-bearing capacity by 15-20 % [7]. Other research efforts have focused on improving the mechanical properties of cement-soil mixtures [8, 9], with

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findings demonstrating that steel fiber reinforcement can enhance compressive strength by 25-40 %. Similarly, studies on cement-soil piles in real-world applications, such as the San Francisco Bridge Expansion Project, confirmed that irregular pile surfaces provide high lateral resistance in sandy soils, particularly when combined with post-grouting techniques [10].

To more understand about the effective of SCCs, the significant reasearchs focused on the geomegy impacts of SCC such as presented by Do H. D. et al., Bolton, M. et al., Nguyen, T.N. et al., Nguyen N. T. Y.. et al., Phan V., and Phu N.Q.V., Quoc L.B., and Vinh P.Q., Thang N. N. et al.., Le Ba Vinh [11-18]. These studies investigated the column length range from 4m to 14m, SCC diameters range from 0.5 to 1m, and the spacing ratio Sc/D range from 2 to 4. Specific data is shown in Table 1. These results showed that the legnth, spacing significantly affect the ground behaviours. These parameters should be treated as adaptive design variables, because the compression modulus of columns treated material generally rises with depth. Optimising these two parameters, therefore, allows the designer to engage the stiffer zones of the column while minimising total column volume and overall cost. However, these studies have not discussed about the settlemenet of the part ground reinforeced by SCCs.

In engineering design, structural stability is one of two critical requirements, and for soft-ground projects, the predicted settlement must remain within allowable limits to secure the long-term safety and serviceability of the facility. It is noted that the length of SCCs is usually shorter than that of the concrete pile because of the lighter loading bearing. In addition, the thick soft soil layers structure the geological properties in the South of Vietnam. Therefore, the SCCs also significantly works in thick soft soil layers, the settlement has to take into the account of the deformation of the ground reinforced by SCCs, (then calling as composite ground), instead of accepting only the settlement of the ground under the SCCs toe as considering the foundation using concrete pile. In practice design, the total settlement includes the settlement of the composite ground, S_1, and the ground under the SCC's toe, S_2, as shown in Figure 1.

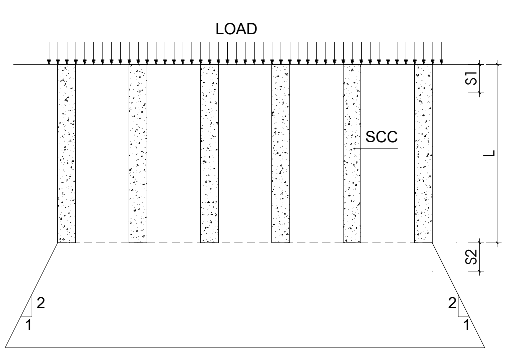


Fig. 1. Settement of the ground using SCCs.

A very simplified equation for the settlement S_1 is used to predict the settlement of reinforced ground [6]. The treated ground is considered a composite medium that responds much like an over-consolidated clay, and considers the effect of the column length. According to this assumption, the column and the surrounding soil share nearly identical deformation along most of the shaft, except for two short segments at the head and toe where load transfer occurs between the column and the ground. Pan et al. and Baker et al. [19, 20] presented the typical idea that the treated ground is a composite medium that responds much like an over-consolidated clay. The settlement response of soil–cement column (SCC) groups is commonly interpreted through a composite-media model in which the treated ground is idealised as a weighted average of the elastic modulus of the columns and surrounding soft soil M_{soil}. A quick-to-use method predicts consolidation settlement beneath embankments supported by floating cement-stabilised columns and a slab [21-22]. It treats only the upper part of the improved layer as fully reinforced; the lower part (thickness H_c) is assumed to compress like untreated clay. Finite-element unit-cell analyses show that H_c can be estimated from simple bilinear relations involving the column area ratio (α) and depth ratio (β).

In this study, a two-dimensional PLAXIS FEM model is established to simulate an embankment resting on soft clay improved with soil–cement columns. The mesh uses axisymmetric unit cells to capture both consolidation and arching effects; the soft clay is described by the Mohr–Coulomb model, whose parameters are calibrated from unconfined-compression tests, whereas the columns are assigned a Non-porous material model. A staged-construction procedure is applied: the embankment fill is placed in lifts, excess pore pressures are allowed to dissipate, and long-term consolidation is computed. Two key geometric variables—column length (L) and centre-to-centre spacing (S_c)—are varied systematically to cover practical ranges. The computed settlements are benchmarked against the widely adopted design equations in TCVN 9403:2012 and TCCS 41:2022 based on Broms & Boman's assumption of the homogeneous-composite model. The results provide a basis for discussing how key geometric parameters—column length, centre-to-centre spacing, and the resulting plan-area replacement ratio—govern the settlement performance of soil–cement column-reinforced ground.

2. Methodology

2.1. Research methods

In this study, the finite element method (FEM) is used to evaluate the influence of soil-cement piles on settlement, for high embankments on soft soil. Using the SCC with a 0.8m diameter, a total of 40 cases have been modelled by considering the various parameters as shown in Table 2

- Column lengths of 8 m, 10 m, 12 m, and 14 m, reflecting current design practice in the Mekong Delta, were analysed.

- The reinforced ground's density was examined by varying centre-to-centre spacing such that the spacing-to-diameter ratio (S_c/D) spanned 2.0, 2.25, 2.5, 2.75, 3.0, 3.25, 3.5, 3.75, and 4.0 in the 2D simulations.

The numerical results are compared with the theoretical calculation, according to TCVN 9403:2012 and TCCS 41:2022. Finally, a discussion and suggestions will be made.

The numerical model is developed using Plaxis software to simulate the construction process of soil-cement piles and embankments. This analysis modelled the soil-cement columns, soft subsoil, firmer stratum, and embankment fill using a Mohr–Coulomb (MC) failure criterion under the assumption of linear elastic–perfectly plastic behaviour [23, 24]. Therefore, this study is based on the Mohr-Coulomb model to consider variations in pile size, spacing between pile centres, pile length, and the thickness of the fill soil layers. This study specifically investigates the effectiveness of soil-cement piles in reinforcing high embankments on soft soil in Phong Dien District, Can Tho City, Vietnam. The research method follows a structured approach, integrating numerical simulation and strength analysis to assess the performance of soil-cement piles on the settlement of composite-ground, the soft soil reinforced by SCCs. Experimental simulation uses finite element calculation software, incorporating key parameters from relevant research documents.

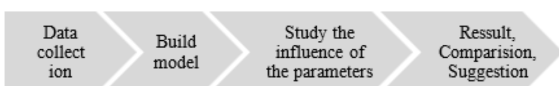


Fig. 2. Implementation process.

For the simplified theory of settlement prediction, Broms and Boman introduced a simple settlement-prediction formula for ground improvement with soil–cement columns. Their model treats the improved zone as a composite material that behaves like an over-consolidated clay while still recognising the finite column length. In this idealisation, the column and the surrounding soil undergo nearly uniform vertical strain along most of the shaft, with load transfer confined to two short zones at the head and toe. Later studies by Pan and Baker adopted the same composite concept, estimating settlement, $\sum S_{group}$ with an equivalent modulus formed from a weighted average of the column stiffness, E_{col}, and that of the soft clay, M_{soil}.

$$\sum S_{group} = \frac{\Delta h \Delta q}{aE_{col} + (1-a)M_{soil}} \qquad \text{Eq.1}$$

$$a = \frac{A_p}{A_s} \qquad \text{Eq.2}$$

Which Δh is the thickness of the ith soil layer corresponding to stress Δq, A_p is the ratio of the sectional area of the pile and A_s the area of the composite soil element.

In practice design, Viet Nam standard of TCVN 9403:2012 and TCCS 41:2022 [25] also present this equation, and propose that the plan-area replacement ratio can be approximately taken as

For SCCs arranged in the square grid, $a = 0.907\left(\frac{D}{B}\right)^2$ Eq.3

For SCCs arranged in the triangle grid, $a = 0.785\left(\frac{D}{B}\right)^2$ Eq.4

Where D is the column diameter and B is the column spacing.

2.2. *Characteristics of materials*

A comprehensive geotechnical survey comprised 2 boreholes, in situ Standard Penetration Tests (SPT) on the project route. Table 2 summarizes overview of the average geological characteristics, the soil profile consists of the following layers: Layer 1: Clay mud, blue-gray, flowing state, thickness 10 m; Layer 2: Clay mixed with sand of blue color, flowing state, thickness 4 m; Layer 3: Brown yellow clay, semi-firm state, thickness 10 m; Layer 4: Clay mixed with sand of brown-yellow color, rigid plastic state, thickness 16 m. It is noted that the Oedometric Young elastic modulus, E_{oed}, has been determined and adjusted to match the corresponding pressure level for each soil layer.

2.3. *Simulation*

The Plaxis modelling for the proposed project. Implement historical and constructive conditions across 8 phases, as presented below. It notes that this study aims to analyse and evaluate the safety factor and settlement of roadbeds under the load due to the self-weight of the embankment soil. As shown in Figure 2 and Table 3, the finite-element model (Plaxis 2D) uses eight construction stages (Phase 0–Phase 8) to simulate the sequence of ground improvement with soil–cement piles (SCPs) and embankment loading. Phase 0 applies the K_0-procedure to restore the in-situ stress field for each soil layer. Phase 1 activates the SCP columns under "staged construction–consolidation" for 60 days, capturing the initial pore-pressure drop after mixing in saturated ground. Phase 2 adds the first 1 m embankment layer in 5 days, and Phase 3 follows with a 60-day consolidation run. The "fill-then-consolidate" cycle is repeated: Phase 4 places the second 1 m layer (5 days) and Phase 5 carries out 60 days of consolidation; Phase 6 adds the third 1 m layer (5 days) and Phase 7 performs a longer, 90-day consolidation to reflect slower drainage under higher fill stress. Finally, Phase 8 conducts a safety analysis with the incremental-multiplier (ϕ–c reduction) method to obtain the global safety factor after three fills and a total consolidation time of 215 days. It is noted that the natural groundwater level is 1.0 m below the ground surface (reference elevation 0.000 m).

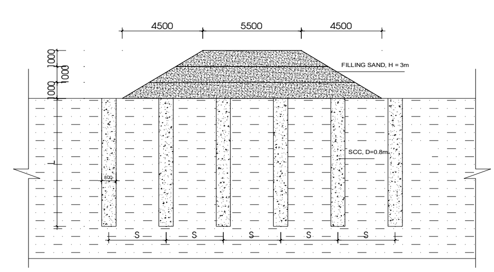


Fig. 3. The embankment cross-section.

3. Results and Discussion

3.1. *Results and discussion*

A total of 40 calculation cases were conducted, comprising one reference case without soil-cement columns and 40 cases with columns of varying lengths (L = 8 m, 10 m, 12 m and 14m) combined with different column spacings (S_c ranging from 1.6 m to 3.2 m). These combinations correspond to S_c/D ratios ranging from 2 to 4. The progress is stopped when the total settlement reaches 10cm, or the ground reaches a critical failure state (yet this condition did not occur in the present results). The primary outcomes analysed the post-consolidation settlement of the ground reinforced by SCCs. The Plaxis model and settlement results are typically shown in Figure 3.

Figure 4 compares the settlement of the composite ground obtained from 2-D PLAXIS FEM analyses with the values calculated in accordance with Vietnamese design standards. Four column lengths were modelled —8 m, 10 m, 12 m and 14 m—while the centre-to-centre spacing Sc was varied from 1.4 m to 3.2 m, giving S/D ratios between 1.75 and 4.0. For each configuration, three output points were extracted: U_{y1} at the outermost column head, U_{y2} at the centreline of the composite block, and their mean U_{y_Aver}, as shown in Table 4.

The PLAXIS-2D dataset, comprising forty combinations of column length L and spacing ratio Sc/D, confirms that settlement growth with spacing is strongly length-dependent. For the shortest columns (L = 8 m) centre-line settlement Uy_2 rises almost linearly from 0.044 m at Sc/D = 1.75 to 0.076 m at Sc/D = 4.0, while edge settlement Uy_1 follows a noisier but still upward trend, climbing from 0.032 m to 0.037 m; their mean value therefore increases from 0.038 m to 0.057 m, a 50 % jump. Extending the columns to 10 m flattens the curve: Uy_2 now spans 0.028–0.036 m and Uy_1 0.020–0.025 m, so average settlement never exceeds 0.051 m even at the widest grid. At 12 m the response is almost insensitive to spacing—Uy_2 hovers near 0.022 m and Uy_1 around 0.015 m—demonstrating the stiffness benefit of toe penetration into the underlying clay layer; the mean stays between 0.018 m and 0.023 m. Lengthening further to 14 m yields only marginal improvement, with Uy_2 limited to 0.023 m and Uy_1 to 0.019 m. Throughout the series the Vietnamese code (TCVN) predicts a uniform, spacing-dependent settlement that is 20–60 % lower than the numerical values for Sc/D ≤ 3.0 and up to 80 % lower at Sc/D = 4.0, reflecting its neglect of shear-lag and toe deformation in widely spaced, short columns.

The numerical results demonstrate a pronounced interaction between column length L and spacing ratio Sc/D on central settlement (Uy_2). With L = 8 m, Uy_2 increases nearly linearly from 0.044 m at Sc/D = 1.75 to 0.076 m at Sc/D = 4.0, indicating that a short column grid loses stiffness rapidly as the soil "windows" widen. Lengthening the columns to 10 m moderates this slope: Uy_2 grows only from 0.028 m to 0.036 m over the same spacing range. The curve becomes almost horizontal for L = 12 m, remaining between 0.022 m and 0.023 m up to Sc/D = 3.5 and reaching only 0.023 m at Sc/D = 4.0; further extension to 14 m reduces Uy_2 by less than one millimetre. These data confirm that once the column toe penetrates the second clay layer (L ≥ 12 m), the composite block's vertical stiffness is governed mainly by the grid density rather than additional length.

The centre-line settlements predicted by PLAXIS (Uy_2) differ markedly from those calculated with the Vietnamese layered-sum formula, and the contrast depends on both pile length and spacing. For the 8 m columns, Uy_2 increases almost linearly from 0.044 m at S/D = 1.75 to 0.076 m at S/D = 4.0. Over the same interval the TCVN value rises only from 0.011 m to 0.050 m, so the code under-estimates the FEM result by 33 mm at the densest grid and still falls short by 26 mm at the widest. For the 10 m columns, the numerical curve is flatter—Uy_2 grows from 0.028 m to 0.036 m—whereas the TCVN curve climbs from 0.024 m to 0.062 m; the two predictions cross at S/D about 2.8, beyond which the code becomes the higher estimate. With 12 m columns, Uy_2 remains between 0.022 m and 0.023 m up to S/D = 3.5 and reaches only 0.023 m at S/D = 4.0, while the TCVN result rises from 0.019 m to 0.075 m; the intersection now shifts to S/D ≈ 2.4. Finally, for the 14 m columns the FEM range is almost constant, 0.015 m to 0.014 m, whereas the TCVN range stretches from 0.019 m to 0.087 m; in this case the layered method already exceeds the numerical value at S/D = 2.0 and overshoots by 46 mm at S/D = 4.0. Plaxis employs the finite-element method based on the stress–strain relationship illustrated in the figure: element stiffness matrices are assembled into a global equilibrium matrix as expressed in Eqs. (4) and Eqs. (5). The mechanical parameters of the Mohr–Coulomb model are used to calculate ground deformations and stresses, so the settlement of the SCC-reinforced block is numerically coupled with the settlement of the soil beneath the column toes. The resulting overall settlement, therefore, captures the complete response of the ground mass. By contrast, the Vietnamese standard partitions settlement into two additive terms (S_1 for the reinforced block and S_2 for the underlying soft layer) and links them only through the vertical stress increment. Because the block is idealised by an "equivalent modulus" that simply averages the pile and soil stiffness, any increase in column length appears only as a thicker stratum in the S_2 summation, inevitably pushing the total settlement upward—an artefact absent from the FEM solution.

$$L^T\sigma + p = 0 \qquad \text{Eq.5}$$

$$\varepsilon = Lu \qquad \text{Eq.6}$$

Where L^T is the transpose of the differential operator, σ is the vector of stress components, p^i is the components of the forces, ε is the strain component, and u is the spatial derivatives of the displacement components.

Clause 9.2 of TCCS 41 : 2022 introduces an empirical factor m (1.1–1.7) to allow for consolidation and creep, yet even when consolidation is included in the FEM model (creep ignored), the numerical settlements remain lower than the code predictions for deep, widely spaced columns. This comparison suggests that the layered-sum approach is adequate for shallow, dense grids but becomes increasingly conservative—up to 46 mm in the present dataset—when columns are long and widely spaced, conditions under which finite-element verification is recommended.

The results in Figure 5 quantify the horizontal displacements that develop along the reinforced block. At the edge of the column grid (U_{x_edge}), the eight-metre column exhibits the most significant outward movement, increasing from 6.68 mm at S/D = 1.75 to 15.96 mm at

S/D = 4.00. Over the same range, the corresponding mid-span displacement, U_{x_mid}, rises from 1.11 mm to 9.71 mm. Ten-metre columns reduce these values substantially: U_{x_edge} grows only from 1.44 mm to 4.15 mm and Ux_mid from 0.50 mm to 1.91 mm. For a twelve-metre column, the edge shift is confined to 0.80–1.87 mm, while the mid-span response remains below 0.74 mm; for a fourteen-metre column, limit U_{x_edge} to 0.41–1.20 mm and U_{x_mid} to 0.17–0.27 mm.

These data explain why central settlements (Uy_2) consistently exceed edge settlements (Uy_1). As spacing widens, the soil prism between columns tends to displace laterally along a shallow slip surface, pushing material outward on both sides of the block; the edge columns act as stiff abutments, so their vertical movement is restrained in comparison with the interior zone. The progressive increase in the ratio of U_{x_edge} to U_{x_mid}, from six at S/D = 1.75 to 1.6 at S/D = 4.00 for the L = 8m case. It demonstrates that differential lateral spread, rather than uniform compression, governs the deformation pattern. Longer piles curtail this mechanism by anchoring the toes in the stiffer underlying clay, thereby limiting horizontal migration to less than two millimetres and, in turn, keeping the centre–edge settlement gap below eight millimetres even when S/D = 4.00.

Table 1. Summarise the research on geometry parameters of SCCs.

Research	SCC properties Diameter D (m) Length L (m) Spacing Sc (m) or S_c/D	Type of research	Conclusions	Noted
Do H. D. et al. [11]	D= 0.8, 1.2 and 2.6 L = 10.5 S_c/D = 1.5, 2.0, 3.0	Numerical (modelling)	The ratio of plan-area replacement value, a, is proposed from 0.2 to 0.62. Proprosing the ratio of S_c/D = 1.5-3 The differential settlement remains small when the spacing ratio Sc/D is set to 2.	A geological profile composed of only one weak clay layer.
Bolton, M. et al. [12]	D =0.5, 0.6, 0.7, 0.8, 0.9, 1.0 L = 19.1 S_c = 2.0, 3.0, 4.0	Numerical (modelling)	For the studied estuarine clay, ultimate bearing capacity increases linearly with the area-replacement ratio, regardless of column spacing. Column spacing Sc can be set based on the soil's initial capacity and the required ratio.	A geological profile comprises three estuarine clay layers with c = 5 kN/m² and f = 23°.
Nguyen, T.N. et al. [13]	D = 0.5, 1.0 L = 4, 10, 15 S_c = 2.0	Numerical (modelling)	Increasing the area-replacement ratio or the length of the soil–cement columns (SCCs) enhances the composite ground's stiffness and raises its consolidation coefficient.	A geological profile comprises only one weak clay layer with c = 1 kN/m² and f = 21°.
Nguyen N. T. Y. et al. [14]	D= 0.6, 0.7, 0.8 and 1.0 L = 10.0, 12.0, 14.0, 16.0 ,18.0, 20.0 and 22.3 S_c/D = 1.5, 2.0, 3.0, 4.0	Numerical (modelling)	The longer piles reduce settlement and make the ground safer until the pile tip reaches the bottom of the soft layer. However, increasing the length after that costs money but gives almost no extra benefit. Proprosing the ratio of S_c/D = 1.5-3	A geological profile composed of three weak-soil layers with a combined thickness of 22.3 m is adopted.
Phan V., and Phu N.Q.V. [15]	D = 0.6 L = 20 S_c = 1.3	Numerical (modelling)	Numerical settlement predictions obtained with PLAXIS 2D deviate from field-monitored values by roughly %, 16 %	A geological profile composed of one weak-soil layer (18m) and three stiff-soil layers (10m)
Quoc L.B., and Vinh P.Q. [16]	D = 0.3 L = 9.0 S_c/D = 3.0	Theory And Field-monitor	Numerical settlement predictions obtained with PLAXIS 3D deviate from field-monitored values by roughly 30 %, The classical theoretical method reproduces the measurements within about 3.5 %. Despite this discrepancy in modelling accuracy, the cement-treated ground clearly exhibits a marked gain in bearing capacity.	A geological profile composed of three weak-soil layers with a combined thickness of 10.5 m is adopted.

Research	SCC properties Diameter D (m) Length L (m) Spacing Sc (m) or S_c/D	Type of research	Conclusions	Noted
Thang N. N. et al. [17]	D = 0.6, 0.8 and 1.0 L = 5.0, 10.0 and 15.0 S_c = 0.8, 1.0 and 1.2	Numerical (modelling)	The CDM-column + geotextile system can be used as a practical solution for bridge approaches in the Mekong Delta:	Calculation of stability in 10 years. A geological profile composed of two weak-soil layers with a combined thickness of 20 m is adopted.
Le Ba Vinh [18]	D= 0.02 L = 0.2 Only 1 column	Experiment	Comparing two settlement-calculation methods (Vietnamese code TCVN 9403-2012 and Chinese code BDJ 08-40-94) shows that laboratory-measured settlements are at least 20 % lower than either code.	

Table 2. Summarise the geometry parameters in this study.

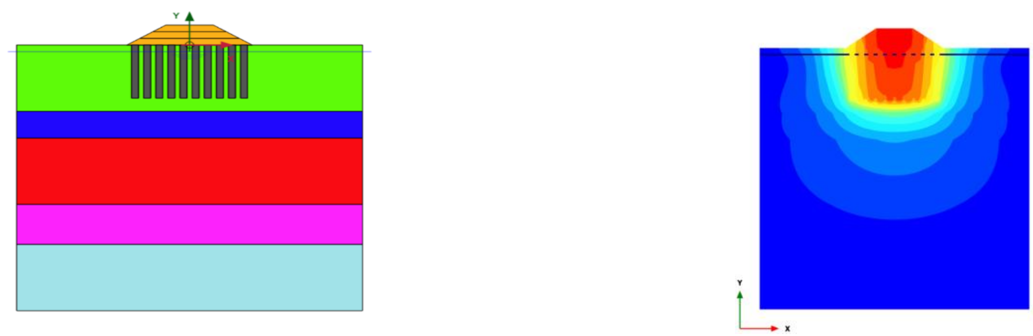
Paramenters	Unit	TCVN and TCCS	Plaxis 2D
Length (L)	m	8 10 12 14	8 10 12 14
S_c/D (D = 0.8m)		2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00	2.00 2.25 2.50 2.75 3.00 3.25 3.50 3.75 4.00

Table 3. Plaxis Input Soil and SCCs Parameters.

	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Filling sand	SCC	Unit
Thickness	H=10	H=4	H=10	H=16	H=10	-	-	m
Model	MC	MC	MC	MC	MC	MC	Linear Elastic	
	Undrained	Undrained	Undrained	Undrained	Undrained	Drained	Non-porous	
γ_{unsat}	15.88	16.60	18.09	19.49	19.64	17	17.09	kN/m^3
γ_{sat}	15.95	16.85	18.34	19.58	19.77	20	-	kN/m^3
E_{oed}	3500	7530	11000	19500	58063	40000	146000	kN/m^2
υ	0.32	0.29	0.32	0.35	0.30	0.30	0.107	
k_x	1.54x10^{-2}	1.21x10^{-1}	3.01x10^{-3}	2.70x10^{-2}	2.70x10^{-2}	1	-	m/day
k_y	6.16x10-3	4.83x10^{-2}	1.20x10^{-3}	1.35x10^{-2}	1.35x10^{-2}	1	-	m/day
c	10.10	11.25	19	34.60	39.50	1	-	kN/m^2
ϕ	3.44	5.07	20	12.08	15.90	32	-	degree

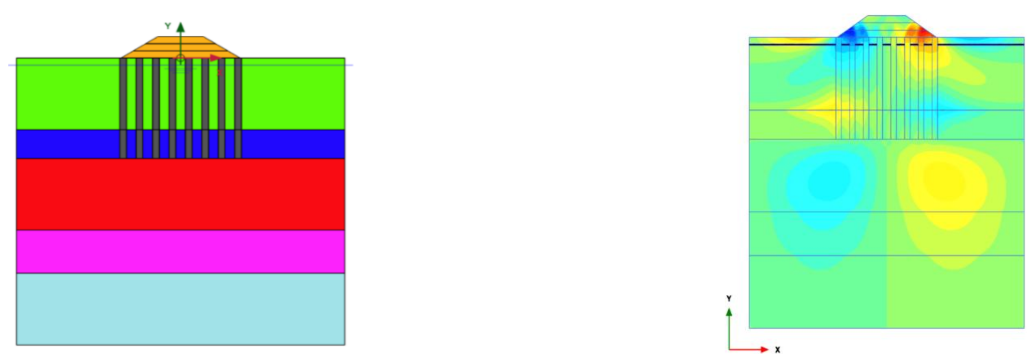
Table 4. The construction stage for the Plaxis 2D model.

Phases	Phases explorer	Computation type	Loading type	Time interval	P-stop	Msf
-	Initial phase	K0-procedure	Staged construction	-	-	-
1	Installing SCCs	Consolidation	Staged construction	60 days	-	-
2	First embankment construction	Consolidation	Staged construction	5 days	-	-
3	First consolidation phase	Consolidation	Staged construction	60 days	-	-
4	Second embankment construction	Consolidation	Staged construction	5 days	-	-
5	Second consolidation phase	Consolidation	Staged construction	60 days	-	-
6	Third embankment construction	Consolidation	Staged construction	5 days	-	-
7	Third consolidation phase	Consolidation	Staged construction	90 days	-	-
8	Safety of analysis	Safety	Incremental multipliers	-	-	0.10



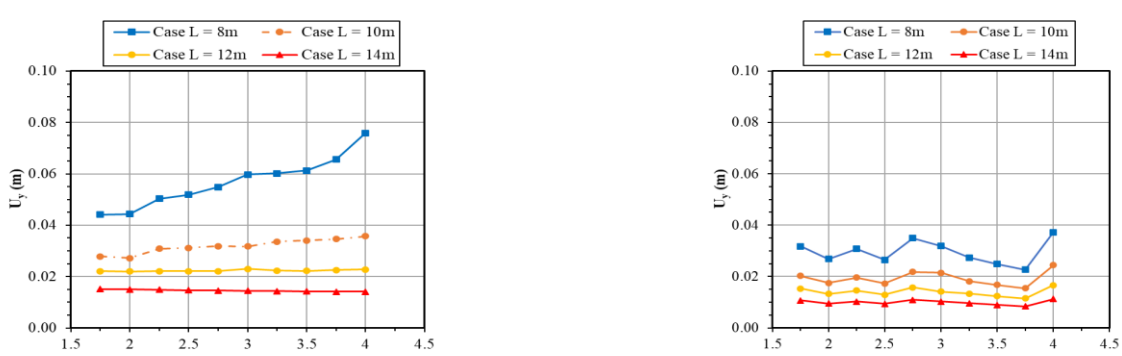
a. Plaxis 2D model　　　　b. Settlement results

Fig. 4. (a) Plaxis 2D model; (b) Settlement results.

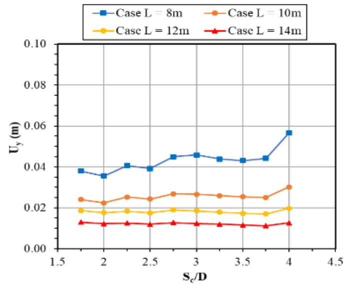


a. Plaxis 2D model　　　　b. Horizontal displacement

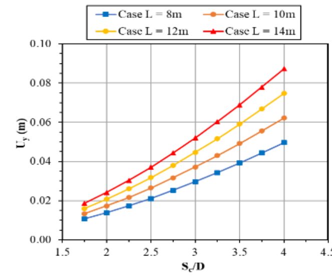
Fig. 5. (a) Plaxis 2D model; (b) Horizontal displacement.



a. Numerical Settlement at the SCC's toe　　　　b. Numerical Settlement at the outermost SCC's toe



c. Average Numerical Settlement at the SCC's toe

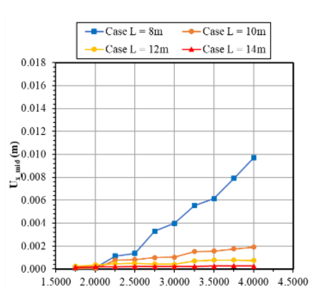


d. Calculated settlement according to TCVN

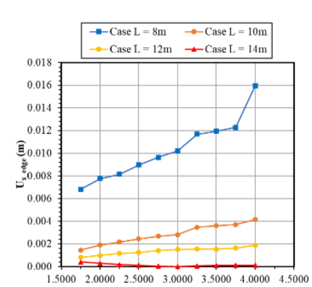
Fig. 6. (a) Numerical Settlement at the SCC's toe; (b) Numerical Settlement at the outermost SCC's; (c) Average Numerical Settlement at the SCC's toe; (d) Average Numerical Settlement at the SCC's toe.

Table 5. Settlement analysed with PLAXIS and calculated according to TCVN.

S_c (m)	S_c/D	Case L = 8m				Case L = 10m			
		U_{y_1} (m)	U_{y_2} (m)	U_{y_Aver} (m)	TCVN (m)	U_{y_1} (m)	U_{y_2} (m)	U_{y_Aver} (m)	TCVN (m)
1.4000	1.7500	0.0318	0.0442	0.0380	0.0107	0.0203	0.0278	0.0241	0.0133
1.6000	2.0000	0.0268	0.0444	0.0356	0.0138	0.0175	0.0272	0.0224	0.0173
1.8000	2.2500	0.0308	0.0503	0.0406	0.0173	0.0196	0.0308	0.0252	0.0216
2.0000	2.5000	0.0265	0.0519	0.0392	0.0211	0.0173	0.0312	0.0242	0.0264
2.2000	2.7500	0.0349	0.0549	0.0449	0.0252	0.0218	0.0318	0.0268	0.0316
2.4000	3.0000	0.0319	0.0597	0.0458	0.0296	0.0214	0.0318	0.0266	0.0371
2.6000	3.2500	0.0274	0.0602	0.0438	0.0343	0.0182	0.0336	0.0259	0.0430
2.8000	3.5000	0.0249	0.0613	0.0431	0.0392	0.0167	0.0340	0.0254	0.0491
3.0000	3.7500	0.0227	0.0656	0.0441	0.0443	0.0155	0.0346	0.0250	0.0555
3.2000	4.0000	0.0372	0.0759	0.0566	0.0496	0.0245	0.0357	0.0301	0.0622
S_c (m)	S_c/D	Case L = 12m				Case L = 14m			
		U_{y_1} (m)	U_{y_2} (m)	U_{y_Aver} (m)	TCVN (m)	U_{y_1} (m)	U_{y_2} (m)	U_{y_Aver} (m)	TCVN (m)
1.4000	1.7500	0.0153	0.0220	0.0187	0.0160	0.0108	0.0151	0.0129	0.0187
1.6000	2.0000	0.0132	0.0220	0.0176	0.0207	0.0095	0.0150	0.0122	0.0242
1.8000	2.2500	0.0145	0.0221	0.0183	0.0260	0.0103	0.0149	0.0126	0.0303
2.0000	2.5000	0.0129	0.0221	0.0175	0.0317	0.0094	0.0147	0.0120	0.0370
2.2000	2.7500	0.0157	0.0221	0.0189	0.0379	0.0110	0.0146	0.0128	0.0443
2.4000	3.0000	0.0142	0.0229	0.0185	0.0446	0.0103	0.0145	0.0124	0.0521
2.6000	3.2500	0.0134	0.0223	0.0178	0.0516	0.0096	0.0143	0.0120	0.0603
2.8000	3.5000	0.0124	0.0222	0.0173	0.0590	0.0090	0.0142	0.0116	0.0689
3.0000	3.7500	0.0115	0.0225	0.0170	0.0667	0.0084	0.0141	0.0113	0.0779
3.2000	4.0000	0.0166	0.0228	0.0197	0.0747	0.0113	0.0141	0.0127	0.0873



a. Horizontal displacement at the toe of SCC's toe



b. Horizontal displacement at the toe of SCC's toe

Fig. 7. (a) Horizontal displacement at the toe of SCC's toe; (b) Horizontal displacement at the toe of SCC's toe.

3.2. Study limitations and future work

This investigation was confined to two-dimensional unit-cell models, so it could not capture plan-layout effects such as the stress redistribution that develops in rectangular or triangular column grids. Extending the analysis to three-dimensional FEM or plane-strain meshes representing multiple columns would allow verification of whether the length–spacing trends reported here remain valid for alternative layouts frequently adopted in practice.

The soil was idealised with the linear-elastic, perfectly plastic Mohr–Coulomb model, chosen for its wide applicability and modest data requirements. While sufficient for a first-order assessment, Mohr–Coulomb cannot reproduce stiffness non-linearity, strain-softening, or secondary compression. Subsequent studies should therefore test advanced constitutive schemes—such as Soft Soil, Soft Soil Creep, or Hardening-Soil—to examine how rate-dependent consolidation and post-yield hardening influence the effectiveness of longer piles and wider spacings.

Finally, performance was benchmarked only against the settlement formulas in TCVN 9403 and TCCS 41, which focus on serviceability (SLS). The research did not evaluate ultimate limit states, cyclic loading, or full pile–soil interaction under failure conditions. Nor did it quantify the load-sharing ratio between columns and surrounding clay, a parameter that governs both bearing capacity and long-term creep. Addressing these aspects will require coupled consolidation-plasticity analyses and comparison with field measurements to establish safety margins under both service and ultimate loading scenarios.

4. Conclusions

This research analyses a forty-case Plaxis 2-D unit-cell series to demonstrate that the coupled action of column length (L) and the normalised spacing ratio (Sc/D) controls embankment settlement over soil-cement columns. From this dataset, the study draws four principal conclusions:.

For short piles (L = 8 m), centre-line settlement rises almost linearly from 0.044 m at Sc/D = 1.75 to 0.076 m at Sc/D = 4.0. Extending the columns to 10 m roughly halves that slope, whereas piles 12 m or longer render settlement nearly insensitive to spacing, confirming that toe penetration into the second clay layer governs vertical stiffness once L ≥ 12 m.

The band Sc/D = 2.0–2.5, combined with L = 12 m, limits centre-line settlement to 0.022–0.027 m and keeps the area-replacement ratio within 10–15 %, providing the optimal balance of performance and cost for Mekong-Delta clays. Grids looser than three diameters should be used only when unavoidable and must be verified by finite-element analysis. To take more economic benefit, the spacing ratio may be extended to 3.0 in the case of surely controlling the settlement and meeting the safety requirements.

The Vietnamese layered-sum method (TCVN 9403 / TCCS 41) underestimates settlement by 20–60 % for dense grids because it neglects shear-lag and toe interaction, yet overestimates by up to 46 mm for long, widely spaced piles. A spacing-dependent correction or FEM verification is therefore necessary when Sc/D exceeds 2.5.

Horizontal-displacement data reveal that widening the grid promotes outward soil flow between columns; for 8-m piles, Ux_edge increases from 6.7 mm to 16.0 mm, whereas Ux_mid grows from 1.1 mm to 9.7 mm, explaining why centre settlements consistently exceed edge settlements. Twelve- and fourteen-metre piles restrict lateral movement below 2 mm, keeping the centre–edge settlement gap under 8 mm even at Sc/D = 4.0.

Role of analytical versus FEM frameworks. In layered analytical theory, column length directly augments the settlement term S_2, so calculated settlements rise markedly with depth. By contrast, the finite-element procedure couples every element through the global stiffness matrix K and satisfies the equilibrium relations expressed in Eqs. (4) and (5); this connectivity mobilises shaft friction and toe resistance more realistically, yielding lower and less length-sensitive settlements than the layered-sum approach.

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