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Research Paper

Stabilizing Soft Soil Foundations using Soil-Cement Columns in Vietnam

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Abstract
Vietnam's infrastructure development faces significant challenges due to the prevalence of deep soft soil deposits, particularly in the Mekong and Red River Deltas. These regions are characterized by high compressibility and low shear strength, necessitating effective ground improvement. These regions are characterized by high compressibility and low shear strength, necessitating urgent and effective ground improvement solutions. This study evaluates the application of soil-cement columns (SCC) as a primary solution for stabilizing these complex foundation systems.
The research focuses on optimizing key design parameters, including the area improvement ratio (α_s), cement content, and layout patterns (square vs. triangular grids). Based on the composite ground theory, the study determines equivalent geotechnical parameters S_u and E_s) for the improved soil zone. Stability is verified through a calculation example assisted by Geo/Slope software
Keywords: *Soft soil stabilization, Soil-cement columns, Settlement control, Geotechnical engineering, Geo/Slope software.*

I. INTRODUCTION

Soil-Cement Columns (SCC) are formed by using specialized equipment to mix cement with in-situ water-saturated soft soil at a predetermined depth. In this process, cement acts as the stabilizing agent, which is thoroughly blended with the saturated soft soil. This triggers a series of physical and chemical reactions within the soil-cement column, causing the soil to harden, thereby increasing its strength and stability, and ultimately improving the load-bearing capacity of the soft ground.

The method first emerged in the late 1960s. Today, soil-cement columns are widely utilized globally for stabilizing soft ground, foundations, embankments, revetments, and culverts. They are also used to reinforce excavation pits, hydraulic retaining walls, and breakwaters, as well as to create seepage barriers and prevent the intrusion of saltwater or contaminated groundwater and soil.

Currently, the nations leading the world in the application of SCC technology are Japan and the Scandinavian countries. According to statistics from the Japan Association, between 1980 and 1986, a total of 2,345 projects utilized approximately 26 million m^3 of soil-cement mixture. Specifically, from 1977 to 1993, the volume of soil stabilized by SCC technology in Japan reached 23.6 million m^3 for both offshore and onshore projects. Currently, this country executes approximately 2 million m^3 of SCC annually.

In China, although the technology was reported as early as 1960, it was not officially applied until 1978. To date, the total volume of soil treated with SCC technology there exceeds 1 million m^3

In Europe, research and application began in Sweden and Finland with studies on lime columns using SLC (Stabilized Lime Column) technology. A notable early application was at Ska Edeby Airport, featuring lime columns with a diameter of 0.5 m and depths exceeding 15 m.

In Vietnam, research into this method began in the 1980s with assistance from the Swedish Geotechnical Institute (SGI), featuring a construction device spearheaded by Dr. Tran Chop.

In 2000, driven by practical demands, the method was reintroduced within the petroleum sector for projects that could tolerate slightly higher settlement levels in exchange for high economic efficiency. During this period, numerous on-site experiments were conducted alongside its application; however, these were primarily research-oriented tests.

Since 2002, projects began utilizing soil-cement columns on soft ground, such as the Ba Ngoi Port project (Khanh Hoa), which involved 4,000 meters of soil-cement columns with a diameter of 0.6 m using dry mixing technology. The method was also used for ground treatment of petroleum storage tanks in Can Tho (tanks measuring 21 m in diameter and 9 m in height). In 2004, soil-cement columns were used to reinforce the foundations of a water plant in Vu Ban District (Ha Nam) and for petroleum storage tanks in Dinh Vu (Hai Phong); all of these projects utilized dry mixing technology.

Also in 2004, the Vietnam Academy for Water Resources received a technology transfer for Jet-grouting from Japan. A research project applied this technology and equipment to study the bearing capacity of single columns and column groups, lateral load capacity, and the influence of cement content on the properties of soil-cement columns. The goal was to apply soil-cement columns for soft ground stabilization and seepage control in hydraulic structures. Key projects included seepage repairs for the Nghe An gate, the D10 gate (Ha Nam), and the Rach Cat gate (Long An).

In Da Nang, soil-cement columns were applied to the Vinh Trung Plaza project in two forms: as diaphragm walls and as a replacement for bored piles.

In Ho Chi Minh City, several projects have utilized soil-cement columns, including the East-West Highway, the Saigon Times Square building, the earth retaining walls at Saigon Pearl on Nguyen Huu Canh Street (District 2), and the stabilization of the Crescent Lake (Ho Ban Nguyet) structures in Phu My Hung (District 7). In Quang Ninh, the Quang Ninh Thermal Power Plant project utilized wet mixing technology (wet spray method). In Hanoi, the method was applied to the Kim Lien road tunnel, the Lang - Hoa Lac Expressway (connecting to the Hoa Lac Hi-Tech Park), and the Ring Road 2 project.

Table 1.1. Summary of Projects Using Soil-Cement Columns in Vietnam

No.	Project Name	Column Diameter (mm)	Total Length (m)	Construction Technology
1	F1 Race Track (Hanoi)	600 - 800	8 - 15	Wet Mixing Method
2	Ben Luc - Long Thanh Expressway	800 - 1000	15 - 25	Wet Mixing Method
3	Bach Dang Bridge (Hai Phong)	600 - 1000	12 - 20	Wet Mixing & Jet Grouting
4	Duyen Hai 3 Thermal Power Plant	800 - 1200	Up to 30	Jet Grouting
5	Tan Vu - Lach Huyen Highway	600 - 1100	15 - 24	Wet Mixing Method
6	Cai Mep - Thi Vai International Port	600 - 1000	18 - 25	Wet Mixing Method
7	Thu Thiem Tunnel & Access Roads	600 - 800	15 - 22	Wet Mixing Method
8	F1 Race Track (Hanoi)	600 - 800	8 - 15	Wet Mixing Method

II. CALCULATION AND DESIGN OF SOIL-CEMENT COLUMNS

2.1. Basis for Soil-Cement Column Calculation

Applicable Calculation Standards and Procedures: The calculation applies the following standards: Procedure for Survey and Design of Road Embankments on Soft Soil **22TCN 262-2000**; Shanghai Municipal Standard for Ground Treatment **DBJ08-40-94**; and Method for Soft Ground Improvement by Cement-Soil Column **TCXDVN 9403:2012**.

General Requirements – Input Data for Geological and Hydrogeological Surveys:

+ Geological strata: Soil classification, physicochemical and mechanical properties of each layer, thickness, and depth.
+ Groundwater conditions: Groundwater levels, ground surface elevation, and borehole locations on the site plan.
+ Geological profiles: Column layout patterns on the site plan.
+ Longitudinal and cross-sections of the road embankment.
+ Experimental data: Binder content (%), binder properties, and the mechanical parameters of the binder.

Design Considerations:

+ Analysis of geological conditions: Specifically evaluating the rationality of the natural ground's geotechnical analysis reports; selecting parameters for design.
+ Project requirements for the soft ground: Road classification, cross-sectional configuration with all elements of the approved plan.
+ Determination of bearing capacity (load-sharing ratio): Determining the column spacing and column length.
+ Binder content and column strength design.
+ Selection of binder grade/type.

2.2. Settlement Calculation

2.2.1. Consolidation Settlement

Consolidation settlement of the foundation soil is calculated using the fundamental formula described below (hereinafter referred to as the Δe method):

$$S_0 = \frac{e_0 - e_1}{1 + e_0} . H \qquad (2\text{-}1)$$

Or by using the following adjusted formulas (hereinafter referred to as the Pc/Cc method):

+ For normally consolidated soil:

$S = \sum \frac{C_c H_i}{1+e_0} log \frac{p_0^i + \Delta p^i}{p_0^i}$ (2-2)

+ For over-consolidated soil:

$S = \sum \frac{C_s H_i}{1+e_0} log \left(\frac{p_0^i + \Delta p^i}{p_0^i}\right)$ if $p_0^i + \Delta p^i < p_c$ (2-3)

$S = \sum \frac{C_s H_i}{1+e_0} \log \left(\frac{p_c}{p_0^i}\right) + \frac{C_c H_i}{1+e_0} log \left(\frac{p_0^i + \Delta p^i}{p_c}\right)$ if $p_0^i + \Delta p^i > p_c$ (2-4)

Where:

- e_0: Initial void ratio corresponding to the in-situ pressure level.
- p_0^i: Effective overburden pressure (self-weight stress) of the foundation soil.
- Δp^i: Vertical stress (increment) induced by the road embankment at the i^th soil layer.
- p_c: Pre-consolidation pressure.
- C_c: Compression index of the soil.
- C_s: Swelling index (or Recompression index) of the soil.
- H_i: Thickness of the i^th soil layer.

2.2.2. Degree of Consolidation

The vertical degree of consolidation for soil layers is calculated based on Terzaghi's theory of primary consolidation, using the following formula:

$T_v = \frac{C_v . t}{H^2}$ (2-5)

Where:

- T_v: Time factor.
- C_v: Coefficient of vertical consolidation.
- t: Time.
- H: Drainage path length (equal to the thickness of the soil layer for single-way drainage; equal to half the thickness of the soil layer for double-way drainage).

2.2.3. Total Settlement

Under the influence of vertical loads transferred from the structure to the composite foundation (soil-cement columns and surrounding soil), the foundation will undergo vertical settlement (S).

$S = \Delta S_p + \Delta S_s$ (2-6)

a) In the case of friction-type columns

The settlement of the soil-cement column section ΔS_p is determined based on the assumption that the stress increment q remains constant throughout the height of the block and that the load within the block does not decrease.

$\Delta S_p = \frac{q_1 H_1}{a_p E_{col} + (1-a_p) E_{soil}}$ (2-7)

Where:

- q_1: The total load acting on the improved soil; q_1= (DL + LL) / A.
- A: The improved area, A = B *L (where B is the foundation width and L is the foundation length).
- DL: Dead load from the embankment acting on a single column.
- LL: Live load from the embankment acting on a single column.
- H_1: Column length.
- a_p: Replacement ratio (area ratio) of the soil-cement columns.
- E_{col}: Deformation modulus of the cement-stabilized column:
  E_{col}= (100 ÷ 300) q_{uck}
- q_{uck}: Unconfined compressive strength of the soil-cement column, determined by testing.
- E_{soil}: Deformation modulus of the foundation soil: E_{soil}= (250 ÷ 400) C_0
- C_0: Unit cohesion of the soft foundation soil.

The settlement ΔS_s beneath the improved soil layer is calculated using the layer-by-layer summation method. The settlement calculation complies with formulas (2-2) through (2-4).

Where:

- $\Delta p^i = q_2$
- q_2: The total load at the mid-depth of the unimproved soil layer.
  $q_2 = \frac{DD+LL}{B+H_2/2}$ (2-8)
- H_2: The depth (thickness) of the unimproved soil layer.

- C_c: Compression index of the soil.

b) In the case of end-bearing columns

- **Settlement of the improved section:**

$\Delta S_p = \frac{P_p}{E} L$ (2-9)

$E = 100q_{uck}$ (2-10)

$P_p = V_p.\gamma$ (2-11)

Where:

- ΔS_p: Settlement of the improved soil section.
- P_p: Load induced by the road embankment.
- L: Column length.
- q_{uck}: Unconfined compressive strength of the column.
- E: Deformation modulus of the column.
- V_p: Active volume of the soil mass.
- γ: Unit weight of the unimproved soil section.

Settlement of the unimproved zone:

$S_c = S_0 \frac{P_c}{P}$ (2-12)

$P = V.\gamma$ (2-13)

$P_c = \frac{V_c.\gamma}{(\lambda+d)^2 - \frac{\pi d^2}{4}}$ (2-14)

$V_c = \frac{\pi}{96} l^2.(9d + 4\lambda).tan\theta + (4-\pi).\left(\frac{\lambda+d}{2}\right)^2.\left\{\frac{\lambda}{2}tan\theta + \frac{1}{3}\left(\frac{\lambda+d}{2}\right)\right\}(\sqrt{2}-\lambda)tan\theta$ (2-15)

Where:

- S_c: Settlement of the unimproved zone.
- S_0: Settlement of the foundation without improvement.
- P_c: Active load on the unimproved zone.
- P: Total load.
- V_c: Pressure on the unimproved zone.
- V: Total pressure.
- l: Spacing between two columns (center-to-center).
- d: Column diameter.
- θ: Friction angle.

2.3. Deep Stability Analysis

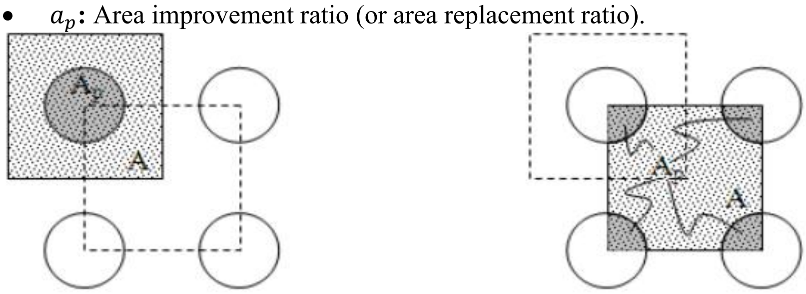
The average shear strength of the soil after improvement with soil-cement columns can be calculated as a composite soil, comprising the shear strength of the ground soil and the cement columns:

$\tau = a_p.C_p + (1 - a_p).C_{00}$ (2-16)

$C_{00} = k.C_0$ (2-17)

In which:

- a_p: Area improvement ratio (or area replacement ratio).



$$a_p = \frac{A_p}{A}$$

C_p: Shear strength of the soil column (or cement-soil column)

C_0: Shear strength of the soft soil

C_{00}: Equivalent shear strength of the unimproved soil portion, calculated for the improved ground case

k: Strength reduction factor (determined from the chart)

τ: Average shear strength of the ground after stabilization

After calculating the shear resistance of the improved ground, the Slope/W software is used to verify the stability of the ground improved with soil-cement columns. The factor of safety against sliding (F_s) is calculated using Bishop's formula as follows:

Formula format:

$$F_s = \frac{\sum \frac{1}{m_a}[C_u.b + (\omega - u.b) tan\theta']}{\sum \omega.sin\alpha} \qquad (2\text{-}18)$$

In which:

- C_u**:** Cohesion (undrained shear strength)
- θ'**:** Internal friction angle
- b**:** Width of the slice
- u**:** Pore water pressure
- ω**:** Weight of the slice
- α**:** Inclination angle of the base of the slice

$$m_a = cos\alpha\left(1 + tan\alpha.\frac{tan\theta'}{F_s}\right) \qquad (2\text{-}19)$$

2.4. Calculation Example for Road Foundation Treatment Using Soil-Cement Columns

Input Parameters

- **Embankment Parameters:**
  - **Stage 1 filling height:** H_d = 3.25 m
  - **Stage 1 filling rate:** 10 cm/day

Design height	H_{tk}	2.75	m
Soft soil thickness	H_{dy}	20.6	m
Embankment height	H	3.25	m
Embankment width	B_n	30	m
Unit weight of fill material	γ	1.85	Ton/m^3
Internal friction angle of embankment	φ	31	^{0}
Cohesion of embankment	c	0	Ton/m^2
Live load	q_{ht}	1.5	Ton/m^2
Total load of embankment and live load	R_{yc}	7.51	Ton/m^2

Soil-Cement Column Design

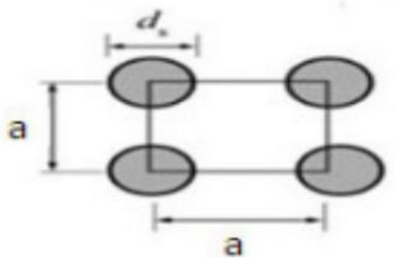
Cement content: 20%

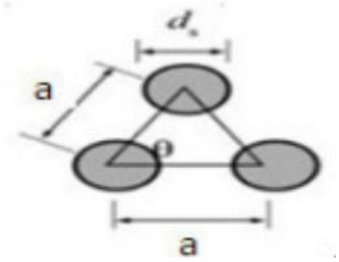
Water/Cement ratio: N/C = 1

Column diameter: d_s = 800 mm

Spacing : a = 1.75 m

Layout Diagrams:





Area Improvement Ratio: α_s= 0.164

Designed Soil-Cement Columns length: L = 14 m

Design of Unconfined Compressive Strength:

$$\boldsymbol{q_{uck} \geq F_s.\frac{\gamma_e.H_e}{a_s}}$$

In which:

Factor of Safety: F_s= 1.20

Therefore:

q_{uck} ≥ 54.93 Ton/m²

Selected design Unconfined Compressive Strength for Soil-Cement Columns: q_{uck} = 80 Ton/m²

Undrained shear strength of Soil-Cement Columns: S_{uck} =40 Ton/m²

Average undrained shear strength of in-situ soil between columns: S_{utb} =1.47 Ton/m²

Elastic modulus of Soil-Cement Columns: E_{suck} =8800 Ton/m²

Average elastic modulus of in-situ soil between columns: E_{stb} =589 Ton/m²

From which, we can calculate Improved Zone Properties
Undrained shear strength of the improved zone:
$S_u = a_s.S_{uck} + (1 - a_s).S_{utb} = 7.8$ Ton/m²
Elastic modulus of the improved zone:

$$E_s = a_s.E_{suck} + (1 - a_s).E_{stb} = 1939.69 \text{ Ton/m}^2$$

Calculation Global stability verification using GeoSlope/W software:
Calculated Factor of Safety: F_{sod} = 1.94
Allowable Factor of Safety: F_{sodcp}= 1.40

Conclusion: Therefore, the road embankment is globally stable!

III. CONCLUSION

In summary, the application of **Soil-Cement Columns (SCC)** offers a highly efficient and sustainable solution for stabilizing soft soil foundations in Vietnam. The primary advantages of this method include:
+ Significant Improvement in Mechanical Properties: SCC effectively enhances the bearing capacity and shear strength of weak soil layers, providing a stable platform for heavy infrastructure.
+ Superior Settlement Control: By creating a composite foundation, this technique minimizes both total and differential settlements, which is critical for the long-term integrity of highways and industrial structures.
+ Time and Cost Efficiency: Compared to traditional piling methods, SCC reduces construction time and material costs by utilizing in-situ soil, thereby eliminating the need for extensive soil replacement or disposal.
+ Environmental Sustainability: The process generates minimal vibration and noise, making it suitable for urban environments. Furthermore, it reduces the carbon footprint by minimizing the transportation of waste materials and imported backfill.
In conclusion, Soil-Cement Columns represent a technically sound and economically viable geotechnical solution, playing a vital role in overcoming the geological challenges of Vietnam's deltaic regions.

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