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Analysis of road settlement on soft soil using 3D finite element method: A case study of the Amata Smart City construction project, Chonburi phase 2

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ABSTRACT

The research explores the settlement patterns of road structures built on soft soil at the Amata Smart City Chonburi Phase 2 through evaluating the performance of soil cement column (SCC) support as a ground stabilizing strategy. Soft clay layers extending from 10 to 14 meters deep make up the project site and create substantial difficulties for bearing capacity and long-term subsurface movement. Although the effectiveness of SCC has been widely studied, limited research has addressed the feasibility of constructing roads without SCC by enhancing the strength of native soft soils. This study aims to fill this gap by evaluating alternative soil improvement techniques. A three-dimensional finite element method (3D-FEM) was analyzed to forecast settlements in two conditions involving road structures with or without SCC support. Predicted settlements received evaluations in construction time and the following 30-year operational span. The existing soil strength was evaluated through a parametric analysis to determine whether strengthening the soil would be a suitable alternative to SCC. Without SCC in road construction, maximum settlements amounted to five times higher than those built with it, specifically in the road center area. An Elastic Modulus of 600 MPa proved to be the most effective strength improvement of the original soil, resulting in a 12.28% reduction in differential settlement and a slight 1.75% reduction in total settlement. Applying suitable soil improvement methods allows road construction on soft soil to remain possible by omitting SCC procedures. SCC remains the most effective method for settlement control; however, road construction without SCC is also feasible when the soft soil subgrade is sufficiently improved. Research findings create knowledge that helps developers achieve better road designs, which balance performance quality and economical construction expenses on soft clay-dominated sites.

Keywords: Soft clay, Finite element 3D, Cement column, Road construction

INTRODUCTION

Road construction projects keep expanding due to land transportation being essential for travel logistics. In the region encompassing Bangkok and the provinces of Chonburi, Samut Prakan, Samut Sakhon, and Samut Songkhram, roads have been constructed on soft clay deposits with a water content of 60 - 140% by weight and a void ratio of approximately 2.0 [1]. Such characteristics within the soil lead to weak shear strength, minimal load capacity, and substantial settlement [2]. The poor permeability of soft clay results in long-term settlement during loading phases, creating major obstacles for construction activities. Differential settlement is a primary cause of road structural damage because it produces both transportation efficiency losses and safety hazards [3].

To mitigate settlement and instability in road construction, soil cement columns (SCC) have been widely implemented as a ground improvement technique [4-11]. The application of this method yields permanent engineered columns which are produced by mixing cement with soil at the construction site to both decrease settlement and increase bearing strength [8, 9]. However, SCC construction involves high costs due to the need for specialized machinery and complex procedures. Project implementation using soil cement columns faces financial difficulties during large-scale projects that demand extensive installation of columns. The high costs of installing SCC have prompted researchers to evaluate alternative soil improvement strategies including subbase stabilization with cement (Soil Cement Subbase) [14-17] which delivers more affordable solutions.

Despite the proven effectiveness of SCC, limited research has focused on the feasibility of constructing roads on soft clay without SCC by strengthening the natural subgrade [14-17]. This study addresses this knowledge gap by evaluating the settlement behavior of road structures built without SCC support, using subgrade improvement techniques as a potential alternative [4-11].

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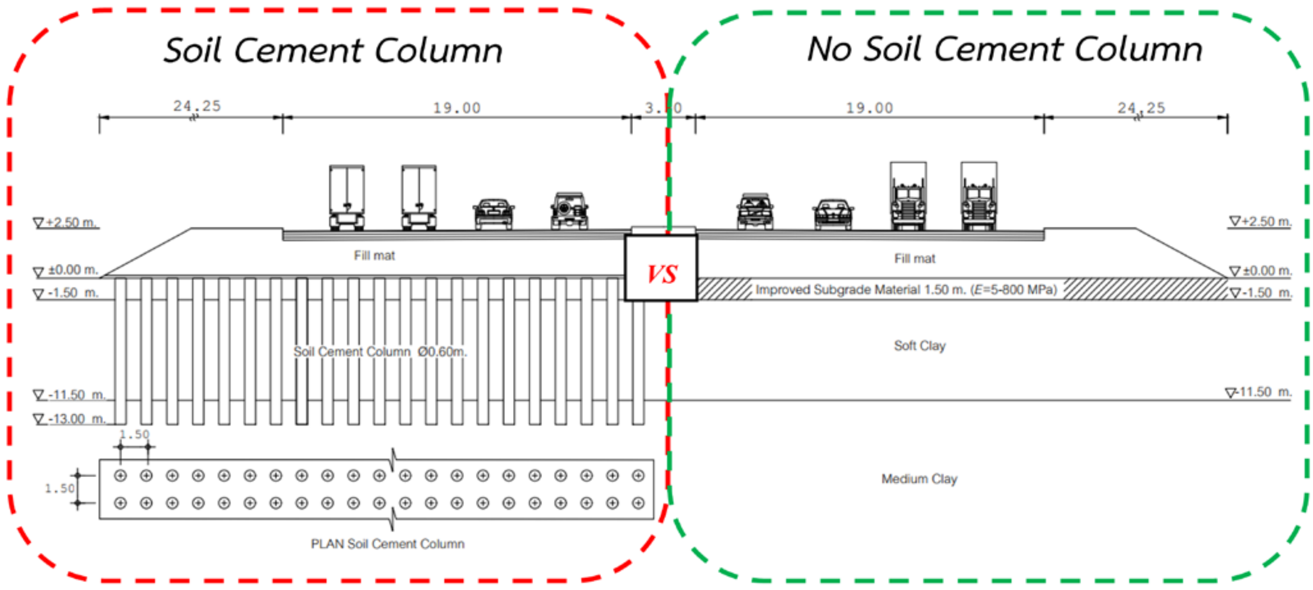

Figure 1 Road structure with and without soil-cement columns.

Multiple studies recently utilized the three-dimensional finite element method (3D-FEM) to study settlement behavior in soft clay because it produces trustworthy results [18-24]. This study applies finite element analysis to simulate the settlement behavior of road structures constructed on soft clay. The examination investigates two road construction methods: soil cement columns and roads without any column support. The main goal focuses on settlement prediction for both construction time and post-construction analysis spanning thirty years. This study investigates the influence of natural soil strength on the feasibility of road construction without SCC. The scope of this research is limited to analyzing settlement behavior under vertical loading only, without considering dynamic traffic loads, environmental effects, or variations in soil stratigraphy beyond the site conditions at Amata Smart City Chonburi Phase 2. The findings obtained from this study are expected to contribute to more effective road planning and design, ensuring long-term structural stability and sustainability.

MATERIALS AND METHODS

The research project evaluates and foretells the settlement patterns in roads and utility systems at various stages of construction without deploying soil cement columns as supporting elements. The analysis evaluates existing soil engineering properties to improve their strength because this strengthens surface load transfer while reducing the likelihood of dangerous differential settlements. A three-dimensional finite element method (3D-FEM) performs the analysis per the cited literature [20,23]. Figure 1 presents the road structure evaluation data between versions with and without soil cement column supports.

A numerical modeling simulation of road settlement patterns on soft clay is conducted through PLAXIS 3D software operations [25]. The research contains two fundamental parts that evaluate (1) settlement patterns in SCC-reinforced road infrastructure and (2) the results of varying existing soil engineering characteristics of Improved Subgrade Material (ISM). A sensitivity analysis on the elastic modulus of ISM, ranging from 5 to 800 MPa, is incorporated to evaluate its impact on settlement behavior.

The Soil-Cement Column (SCC) method involves deep mixing in-situ soft clay with cement to form cylindrical columns that enhance bearing capacity and reduce compressibility. The Improved Subgrade Material (ISM) technique improves shallow soil strength by mixing cement with existing subgrade material and compacting it in layers to form a stabilized mat beneath the road structure.

Finite element model

The road structure in its initial model features soil cement columns with 0.60 meters diameter lasting 13.00 meters and spaced at 1.50 meters intervals. The simulation evaluates both the settlement patterns of structures as well as their performance characteristics. The second part of the analysis makes alterations to enhance the strength characteristics of the existing soil materials. The settlement evaluation between the SCC-stabilized road design and optimized subgrade composition will identify the best solution for road infrastructure development.

A symmetric boundary condition exists for this project road because its 80 meters of total width demonstrates two-sided symmetry, allowing researchers to attain modeling accuracy while minimizing complexity. The model analysis takes place by evaluating symmetrical *YZ* plane boundary conditions at the road centerline while enforcing $U_x = 0$ to restrict *X*-direction movement. A fixed boundary condition has been assigned to

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the model base to simulate realistic soil responses accurately. The areas that display expected substantial settlement receive mesh refinement as a technique to improve analysis precision. The groundwater table was located 1.5 meters below the ground surface and modeled as a hydrostatic line, with pressure increasing linearly with depth.

The overall dimensions of the model used in this study are 100 meters in width, 250 meters in length, and 26 meters in depth from the ground surface. Mesh refinement was applied in areas expected to exhibit significant settlement, particularly near the road structure and soil improvement zones, with the refined element volumes ranging approximately from 0.2 to 0.6 m³ per element to enhance the analysis precision. The finite element model consists of 684,956 nodes and 326,194 elements, as illustrated in Figure 2.

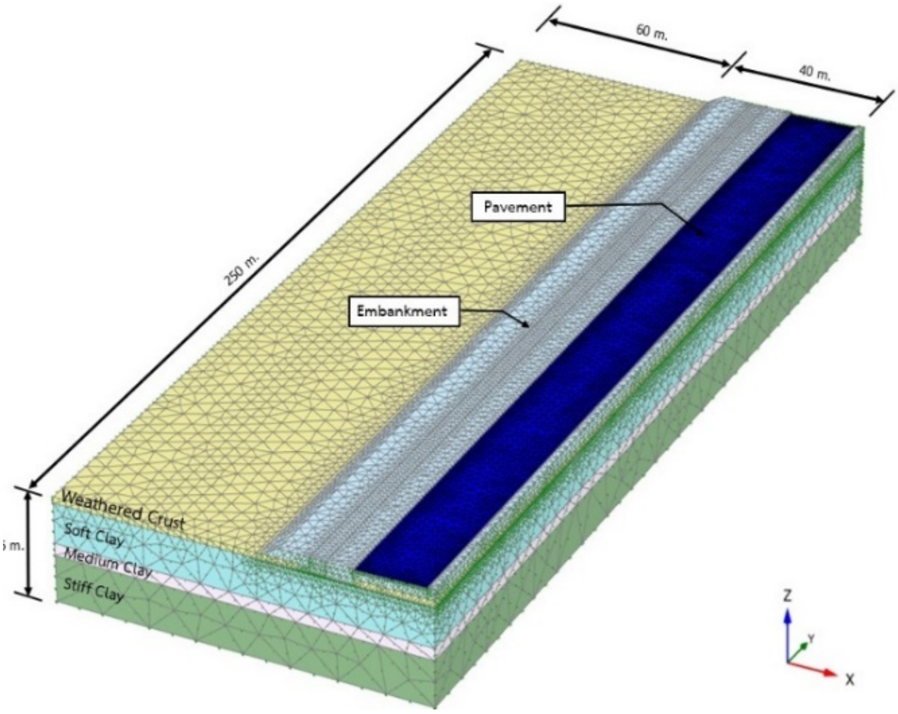

Figure 2 Geometry of the problem and 3D Finite element mesh used in this analysis.

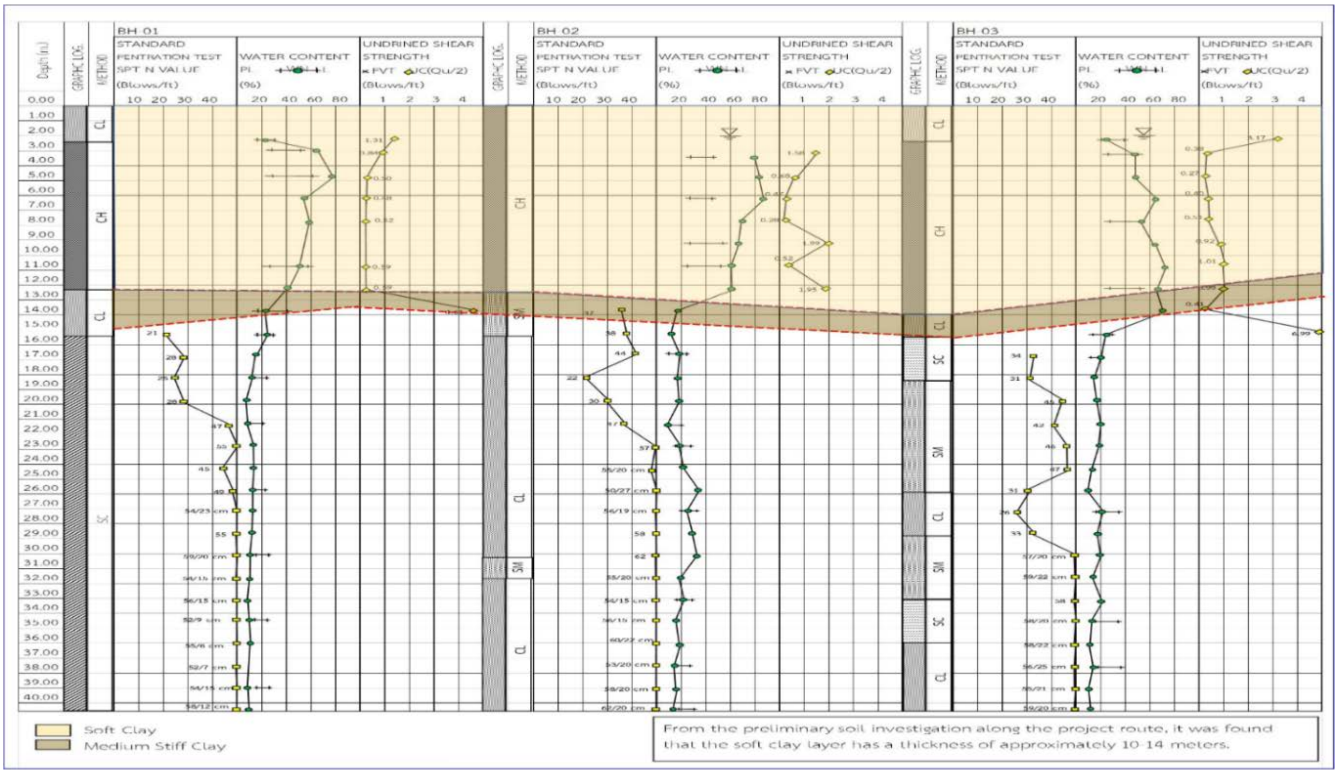

Figure 3 Borehole data for BH-001, BH-002, and BH-003.

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Subsoil data and parameters

Soil engineering properties evaluations took place at different sites (BH-001, BH-002, BH-003) found inside the Amata Smart City Chonburi Phase 2 development. The project site rests upon a soft clay layer which extends from 10 to 14 meters below the ground surface, as the yellow section shows in Figure 3, indicating the subsurface conditions.

For numerical analysis, the soil layers were classified as follows: the weathered crust layer, with a thickness of 1.50 meters, was identified from 0.00 to -1.50 meters; the soft clay layer, with a thickness of 10.00 meters, was found between -1.50 and -11.50 meters; the medium clay layer, with a thickness of 3.00 meters, was observed from -11.50 to -14.50 meters; and the stiff clay layer, with a thickness of 11.50 meters, was present from -14.50 to -26.00 meters.

The input parameters for finite element modeling were based on previously validated values from a nearby project with similar subsoil characteristics, where calibration against long-term field data was successfully performed Malai et al., 2022 [23]. The researchers applied the soft soil model to simulate the soft and stiff clay layers. The analysis employed the Mohr-Coulomb Model to simulate soil behavior using parameters from Table 1. Long-term settlement was evaluated using coupled consolidation analysis, simulating mechanical deformation and time-dependent pore water pressure dissipation in the soil.

For the Soil Cement Columns (SCC), concrete pavement slabs, and asphalt concrete layers, the Linear Elastic Model was adopted, with material parameters referenced from a reliable study on the intercity highway connecting Highway No. 7 and Bang Na-Trat Highway [10, 23], which is geographically close to the project site.

The differential settlement was determined using Equation (1),

$$\Delta S = S_{center} - S_{corner} \quad (1)$$

where S_{center} and S_{corner} represent the settlement at the center and left edge of the roadway, respectively. The maximum settlement was observed at the center of the road, at X = 100 meters.

Table 1 Constitutive model parameters for each type of material.

Properties	Wea Crust	Soft Clay	Stiff Clay	Dense Sand	Fill Mat.
Model	MC	SS	SS	MC	MC
Type	D	U	U	D	D
γ_{unsat} (kN/m^3)	16	16	18	20	17
γ_{sat} (kN/m^3)	18	16.5	19	20	20
k_h (cm/d)	0.4	0.08	0.08	80	173
k_v (cm/d)	0.2	0.04	0.04	40	86
E (MPa)	5	-	-	100	40
n	0.25	0.30	0.25	0.25	0.25
λ^*	-	0.11	0.085	-	-
K^*	-	0.056	0.017	-	-
C' (kPa)	10	10	15	0	5
$Ø'$ (deg.)	12	8	30	39	31
OCR	-	1.2	1.65	-	-
k_0	0.65	0.75	0.65	0.37	-
f_a (kPa)	10	39	60	-	-

MC = Mohr Coulomb as yield criteria,
SS = Soft Soil Model, D=Drained, U= Undrained

Simulation Process

The simulation started by calculating initial stress conditions through the coefficient of earth pressure at rest (K_0) value for each soil stratum. The simulation of embankment construction proceeded by adding 2.5 meters of fill material distributed in successive layers of 50 centimeters each. The road structure followed the construction design by including key components for base course, subbase layer [15], pavement, and soil cement columns using the parameters outlined in Table 2.

This study did not explicitly model dynamic traffic effects such as cyclic loading and vibration. The traffic load of 10 kN/m² was modeled as a static uniform load to approximate the long-term average loading effect, a common simplification in consolidation settlement analysis. A 30-year operational simulation occurred while applying a traffic load onto the pavement surface. The research evaluated three models consisting of (1) No Cement Columns (NCC) that excluded soil cement stabilizations, (2) Soil Cement Columns (SCC) employed as load-bearing features, (3) Improved

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Subgrade Material (ISM) strengthened the weathered crust layer to enhance its stiffness properties. The Elastic Modulus values of the enhanced material in the ISM case were changed between 5 MPa and 800 MPa. Based on preliminary analysis, variations in other constitutive model parameters had negligible effects on the embankment's total and differential settlements. Therefore, only the elastic modulus of the ISM was varied during the sensitivity analysis, while other parameters, including those of the Weathered Crust layer, were kept constant.

A comparison of settlement values and differential settlement between three construction approaches occurred after 30 years of road operation gave information about their long-term performance.

RESULTS AND DISCUSSION

Improved subgrade material (ISM)

Figure 4 illustrates the relationship between The Elastic Modulus of the Improved Subgrade Material (ISM) and settlement values. An increased Elastic Modulus value results in continuous settlement reduction. The settlement values decrease notably throughout the pressure range from zero to four hundred MPa. Beyond 500 MPa Elastic Modulus value the settlement reduction rate becomes slower, and additional material strength increases will not produce considerable settlement reduction benefits.

The blue dashed line shows that the differential settlement quantity decreases when the Elastic Modulus value increases. The data shows that differential settlement decreases intensively during the Elastic Modulus range from 0-200 MPa. The effectiveness of differential settlement reduction experiences decreased performance while the Elastic Modulus remains between 400 MPa and 800 MPa. Under laboratory conditions, the Elastic Modulus of ISM is the main controlling factor for settlement and differential settlement reduction through its elevated values.

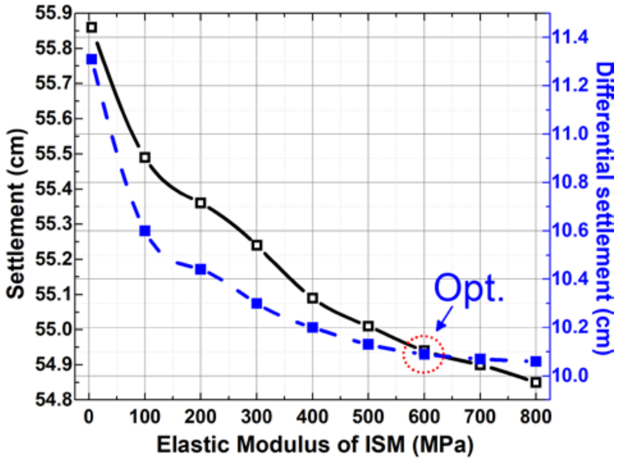

Figure 4 Comparison of Elastic Modulus with Differential Settlement and Maximum Settlement of the Road.

Table 2 Details of Structural Modelling in FEM Analysis.

Type of Structure	Model	Thickness/Diameter (m)	Unit Weight (kN/m³)	*E*, (kPa)
Asphalt concrete	P	0.05	5	2.5×10^6
Concrete Pavement	MC	0.15	24	2.4×10^7
Base	MC	0.15	20	6.6×10^4
Sub Base	MC	0.15	20	2.5×10^4
Soil Cement Column	EP	0.60	8	3.6×10^5

P = Plate, EP = Embedded pile

Beyond an Elastic Modulus exceeding 600 MPa the settlement reduction effectiveness becomes marginal because the additional stiffness will not enhance the performance substantially.

The optimal value (Optimal Point, Opt.) was identified at approximately 600 MPa. The optimum point is determined at the intersection of the two curves, representing a balance between differential settlement reduction and control of total settlement. At this modulus, the analysis indicated a 12.28% reduction in differential settlement and a 1.75% reduction in total settlement. Emphasis is placed on the reduction of differential settlement, as it is considered more critical to the structural performance and long-term serviceability of the road. The Differential Settlement Ratio, which represents the degree of road deflection, is expressed in Equation (2).

$$\Delta S_{ratio} = \frac{\Delta S}{Span(L)} \tag{2}$$

When Span (L) represents the width of the road, which in this study is 19 meters.

The ΔS_{ratio} is found to be 1/190. Even with further improvements in soil stiffness, no significant benefits in settlement reduction are observed. Therefore, the Elastic Modulus of ISM should be selected at the optimal value (600 MPa) to effectively reduce both settlement and differential settlement while avoiding unnecessary cost increases.

The road displacement testing involved three scenarios, which included testing with soil cement columns (SCC) and without soil cement columns (NCC) alongside testing with improved subgrade material (ISM) that used an Elastic Modulus set to 600

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MPa as shown in Figure 4. Analysis of the settlement patterns revealed that the red line representing SCC data demonstrated the smallest distance between points in all investigated road areas, thus proving its potential for settlement reduction. Within the 90 - 100 meter area, the NCC case (black dashed line) demonstrated the largest displacement because this section included the road center, where significant settlement occurred. Irregular patterns combined with fluctuating movements characterized the displacement results in the NCC case.

The damaged structures in the blue line ISM case showed equivalent settlement patterns to NCC yet displayed enhanced stability, proving that ISM soil improvement methods outperformed unenhanced NCC soil foundations.

ISM treatment of existing soil is a practical solution for controlling differential settlement in areas with soft soil. ISM offers cost-effective road maintenance through its budget-friendly solution with stable roadway conditions against SCC standards. ISM represents a suitable option when cost reduction stands as a primary requirement. The analysis presented in this study exists only as an initial evaluation but needs further evaluation to determine long-term settlement risks. A complete geotechnical investigation with a thorough design for the road structures must be performed to determine appropriate site-specific solutions.

Characteristics of road settlement

Three road conditions were examined through displacement evaluations in Figure 5, including SCC, where soil cement columns existed, and NCC, which had no soil cement columns, and ISM with an Elastic Modulus set to 600 MPa. The analysis results show that Soil Cement Columns (red line) delivered the minimum displacement of the road surface through all sections, thus confirming their effectiveness in reducing settlement. Soil cement columns (black dashed line) produced the maximum settlement result that peaked within the 90-100 meter zone, corresponding to the road center where significant subsidence happened. The displacement patterns in the NCC case showed mixed and unpredictable results throughout the experiment.

The case using improved soil by ISM (blue line) displayed displacement behaviors similar to those of NCC but achieved higher stability, demonstrating that soil modification from ISM helped lower settlement differences over NCC since NCC lacked any enhancement measures.

Using improved existing soil through ISM presents itself as a well-established method to reduce differential settlement in regions with soft soils. The road stability remains acceptable when this approach is used instead of SCC, and it generates cost savings. ISM proves to be a suitable, cost-efficient solution within projects requiring financial savings. The paper delivers initial analysis results, but further evaluations must be conducted to determine potential dangers related to long-term settlement behavior. A thorough geotechnical analysis and complete road design evaluations must be performed to determine site-appropriate solutions.

Although the effectiveness of soil cement columns (SCC) has been widely validated [1-13], limited studies have explored the feasibility of constructing roads on soft clay without SCC by strengthening the natural subgrade [15-17]. This research addresses the identified gap by evaluating settlement behavior.

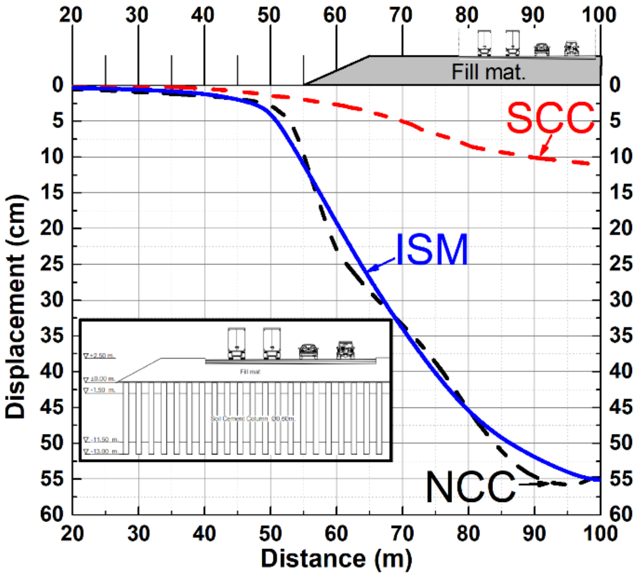

Figure 5 Road displacement comparison between cement deep mixing piles (SCC), no cement deep mixing piles (NCC), and Improved Subgrade Material (ISM) under alternative subgrade improvement strategies.

Long-term settlement of the road

A 30-year operational period revealing the road settlement is presented in Figure 6. The road structure received its maximum settlement of 11 centimeters within the center, while its minimum settlement of 3 centimeters occurred at the edge of the embankment after 30 years in operation.

The maximum settlement for the ISM case developed at the center of the road increased from 30 to 55 centimeters throughout 3, 5, 10, 20, and 30 years of operation. The ground experienced a 5-centimeter yearly increase in settlement throughout the initial 3 to 10 years. The settlement rate from years 20 to 30 steadily declined before reaching a stable position.

A clear difference exists between the settlement patterns of SCC and ISM because of the variations in differential settlement behavior. Overall, the settlement remains better in the SCC design, yet the ISM design experiences higher levels of settlement.

Road structure deterioration becomes less likely due to improved soil quality, which increases stability

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and reduces unacceptable differential ground settlements. The selection of soil improvement techniques needs careful assessment between cost expenses and structural stability factors to match the site conditions for environmental and geotechnical needs.

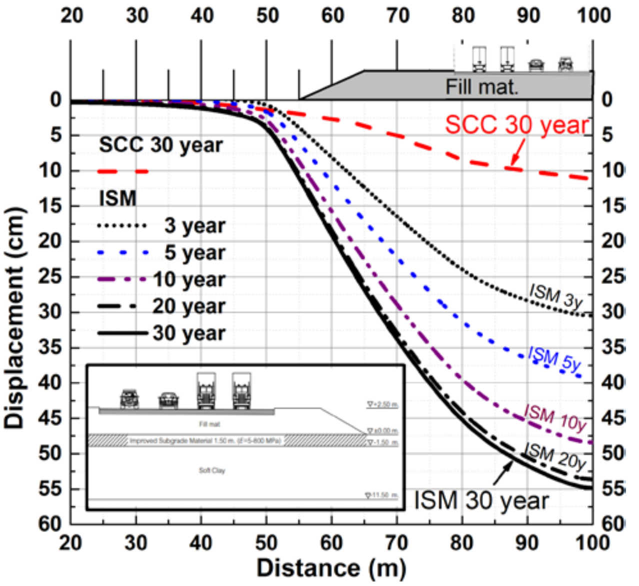

Figure 6 Road displacement comparison between soil cement columns (SCC) and improved subgrade material (ISM) over a 30-year operational period.

CONCLUSIONS

The study investigated settlement patterns of road structures built on soft clay sections within the Amata Smart City Chonburi Phase 2 Industrial Estate. The research followed a two-step approach by analyzing (1) SCC-supported roads and comparing them with (2) NCC-supported roads. The study assessed existing soil layer improvement (ISM) as a substitute for boosting soil strength and decreasing differential settlement. The research results demonstrate the following essential points:

1. The settlement rate of roads without soil cement column support (NCC) was five times higher than that of roads with SCC support, with the maximum settlement occurring at the center of the road.

2. Improving the existing soil layer (ISM) by increasing the elastic modulus (Elastic Modulus) showed that the optimal value for minimizing both settlement and differential settlement was 600 MPa, which provided the most effective results.

3. The long-term settlement behavior analysis indicated that the SCC-supported road structure exhibited a maximum settlement of approximately 11 cm at the center of the road. In contrast, the ISM-supported road structure experienced a maximum settlement of 55 cm over 30 years.

4. The trend of differential settlement demonstrates that greater settlement reduction is achieved in roads supported by SCC, whereas higher settlement is observed in roads utilizing ISM.

The research evidence demonstrated that soil cement columns (SCC) proved to be the most optimal approach to minimize road settlement problems while upholding structural integrity. Improving existing soil layer (ISM) is a practical substitute that lowers construction expenditures. The present investigation serves as a preliminary assessment thus, more analysis of settlement risks needs additional investigation. A complete geotechnical assessment and road structure design work must be carried out to confirm compatibility with local site conditions. Furthermore, this study considers only a static uniform traffic load. Future research should incorporate dynamic traffic effects, including cyclic loading and vibrations, to gain deeper insights and more accurately assess both short-term and long-term settlement behavior. Additionally, advanced constitutive models such as the Soft Soil Creep (SSC) are recommended to capture time-dependent behavior better.

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