Performance Comparison of Ground Improvement Methods for Settlement Reduction (Case Study: 5000M³ Fuel Tank)

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Abstract — This study compares the effectiveness of three soil improvement methods: Stone Column (SC), Modular Grout Column (MGC), and Deep Soil Mixing (DSM), in reducing settlement for a 5000 m³ fuel tank. Using 2D numerical modeling, the settlement reduction for each method was analyzed. MGC was the most effective, achieving 52% settlement reduction, followed by SC (47%) and DSM (39%). MGC's superior performance is attributed to its high stiffness and greater load transfer capacity. These findings emphasize the importance of selecting the appropriate soil improvement method based on site-specific soil conditions. Increasing column diameter is also recommended to enhance settlement mitigation. In conclusion, MGC offers the most effective solution among the tested methods for mitigating foundation settlement in soft soil, providing critical guidance for geotechnical design engineers.

Keywords: deep soil mixing; modular grout column; settlement reduction; soil improvement; stone column.

I. INTRODUCTION

The construction of infrastructure on soft soil presents significant challenges in civil engineering due to the inherent characteristics of soft soils, which often have low bearing capacity and slow consolidation behavior (Pratiwi & Abdurahman, 2024). These challenges are particularly critical for projects like fuel storage tanks, where long-term stability and safety are essential. Soft soils, as the foundation material, require improvement to minimize the settlement that may occur during the operational phase (Aslam & Gofar, 2022).

A fuel tank is a critical structure that requires careful consideration of the foundation's stability to ensure its proper function and long service life. Foundations subjected to heavy loads can lead to structural changes in the soil (deformation), resulting in settlement that can cause the tank's position to become unstable, thus compromising its ability to hold the intended volume of fuel. (Contesa et al., 2019). To address these issues, various ground improvement techniques have been developed. Among them, stone columns, modular grout columns, and deep soil mixing are three widely applied methods that offer distinct mechanisms for improving soft soil performance. Each method has advantages and limitations, and their effectiveness often depends on project-specific conditions, particularly in terms of settlement reduction.

This study therefore focuses on a comparative analysis of stone columns, modular grout columns, and deep soil mixing, with a case study of a 5000 m³ fuel storage tank. The scope is deliberately limited to these three methods to allow a more detailed evaluation of their effectiveness in reducing settlement. The significance of this research lies in its contribution to guiding more informed engineering decisions, particularly for projects constructed on soft soils. By providing a comparative evaluation, the outcomes are expected to enhance the understanding of settlement reduction strategies, ultimately supporting safer, more cost-efficient, and resilient infrastructure development.

By evaluating and comparing the effectiveness of different methods, this research can provide valuable insights into their practical applications. The outcomes could lead to better design decisions, improving both the safety and cost-effectiveness of future infrastructure projects.

II. LITERATURE REVIEW

Soft soil is a type of soil with low bearing capacity, typically characterized by high moisture content and very low permeability, which often presents challenges in civil engineering construction. (Fatimah & Hamdhan, 2024). Additionally, soft soil often exhibits low Standard Penetration Test (SPT) values, typically ranging from N-SPT 0 to 5, indicating that the soil has very low strength (Fatimah & Hamdhan, 2024).

Thorough investigation and control are essential to prevent stability issues and excessive long-term settlement, which could damage structures built on such soils. One of the major challenges posed by soft soils is significant settlement under load. To mitigate this problem, soil improvement techniques must be applied (Pranata et al., 2019)

Stone columns are a soil improvement method that involves replacing a portion of the soft or weak soil at the project site with granular material, such as crushed stone, which is subsequently compacted to form vertical columns within the soil. This process aims to enhance the soil's bearing capacity and reduce excessive settlement of the structures to be constructed above it (Somantri et al., 2021).

The modular grout column method is a soil improvement technique that involves inserting concrete columns into the ground using a specialized auger, without producing soil waste. This method has been widely used in infrastructure projects such as airports, highways, and railways due to its fast installation process, minimal vibration, low noise levels, and ability to prevent water accumulation (Efendi et al., 2025).

Deep soil mixing (DSM) is a technique used to improve soil strength by incorporating binders. This in-situ soil modification process involves injecting either wet or dry binders into the soil, which are then mechanically mixed with soft soils, such as clay, peat, or organic soils, using a rotary mixing tool (Tyas et al., 2022).

In the design of soil improvement methods, several key parameters are crucial to consider, as they directly dictate the performance and cost-effectiveness of the project. These parameters serve as the fundamental basis for conducting detailed technical analyses, accurately calculating the soil's bearing capacity, and precisely estimating settlement. The main factors that must be carefully determined include the diameter dimensions of the improvement method, which significantly influences the stiffness and load transfer capacity; the installation depth, which must penetrate sufficiently into the competent sub-stratum to ensure stability and prevent punching failure; the spacing between improvement elements (defining the area replacement ratio), where closer spacing leads to better load sharing and superior settlement control; and the installation pattern in the field, which affects how loads are optimally distributed beneath the structure. Each of these factors is highly interconnected and cannot be determined in isolation. Changes in one parameter often necessitate adjustments in another to maintain the desired level of settlement mitigation. Therefore, successful soil reinforcement relies on a delicate balance and optimization of these geometric variables based on site-specific geotechnical data. (Rohmah & Hamdhan, 2021).

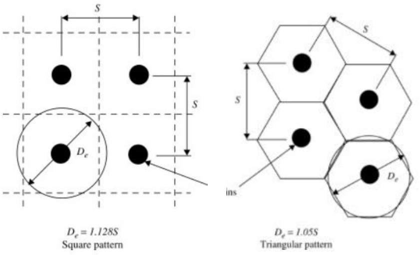

Figure 1. Various installation patterns and formulas

Source: (Michael & Kawanda, 2020)

Triangular pattern is more efficient in terms of the spacing between stone columns compared to the square pattern. This configuration results in a closer arrangement of columns. (Prasojo & Dr.Ir. Hendriyawan, 2017).

In evaluating the effectiveness of various soil improvement methods, uniformity in technical specifications, such as column depth, spacing between columns, and column diameter, across methods is crucial. Comparisons between methods must be conducted using consistent parameters to ensure that the results are valid and reflect performance differences due to the methods themselves, rather than variations in the technical specifications used. Therefore, the application of a consistent methodology is essential to obtain objective and accurate results in soil improvement evaluations (Bryson & Naggar, 2013).

To determine the settlement values of each soil improvement method, a 2D analysis model is used. The reason for using the 2D model is that both 2D and 3D models yield similar results, making the 2D approach more efficient for this application (Gaber et al., 2018). The modeling approach employed for this analysis is based on the axisymmetric unit cell model, which is suitable for the case under study, where the tank is circular in shape. This approach simplifies the analysis while still providing accurate results for settlement prediction.

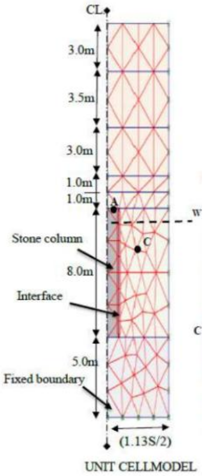

Figure 2. Unit cell axisymetry model
Source: (Michael & Kawanda, 2020)

The unit cell model is widely used to design and evaluate the performance of columns. In this model, a single column is represented along with an equivalent circular zone of influence. For triangular and square column patterns, the equivalent diameters are 1.05 and 1.13, respectively. The spacing (S) refers to the center-to-center (c/c) distance between columns, which plays a crucial role in determining the overall effectiveness of the soil reinforcement (Gaber et al., 2018).

III. METHOD

This research employs a descriptive- quantitative, aimed at systematically describing and analyzing the effectiveness of various soft soil improvement methods. The study will focus on a performance comparison of these methods in reducing settlement, taking into account the relevant technical variables. The findings are expected to provide a clear insight into the relative effectiveness of each method based on the established parameters.

The design of this research employs an analytical approach using 2D modeling as the primary tool to compare the effectiveness of various soil improvement methods. The methods analyzed in this study include Stone Column, Modular Grout Column, and Deep Soil Mixing, focusing on technical analysis to evaluate the performance of each method in reducing settlement.

A. Data Analysis

The data analysis performed in this research is illustrated in Figure 3, outlining the following steps:

1. Soil data interpretation;
2. Settlement analysis without the application of soil improvement;
3. 2D numerical modeling;
4. Settlement reduction analysis with soil improvement.

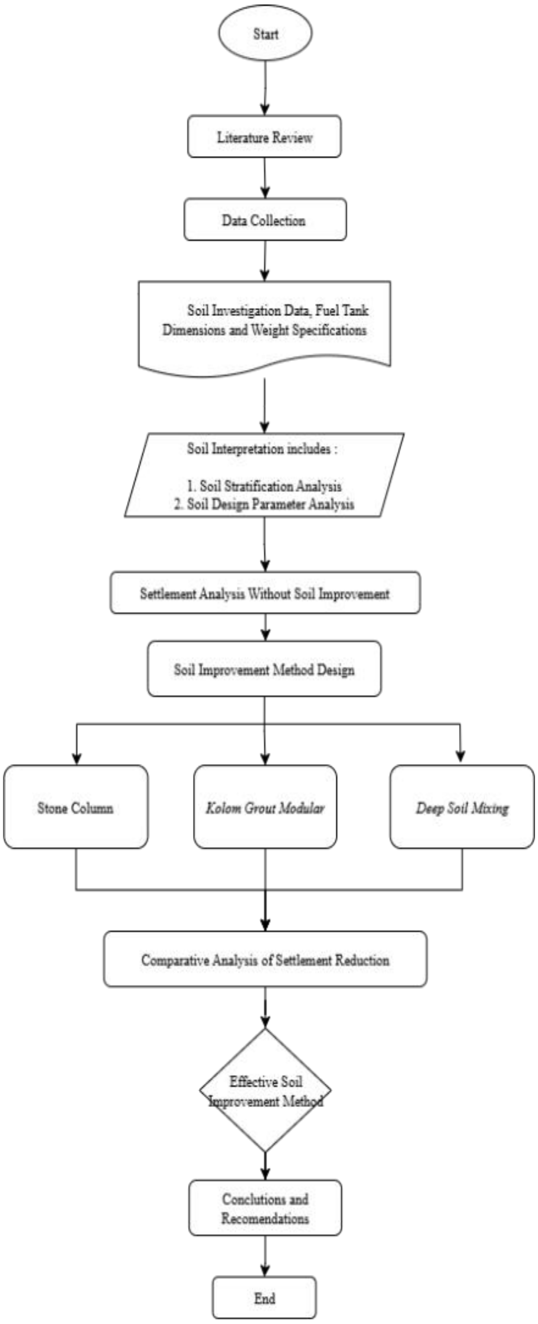

Figure 3. Flowchart

B. Numerical Modeling

1. Domain Scheme and Boundary Conditions

For the domain analysis, an axisymmetric unit cell model was employed, where the outer edge distance to the column group is set at 1.05 times the center-to-center spacing (S/2). The boundary conditions, including displacement and flow, were automatically determined by the software based on the project parameters configured through the Project Manager.

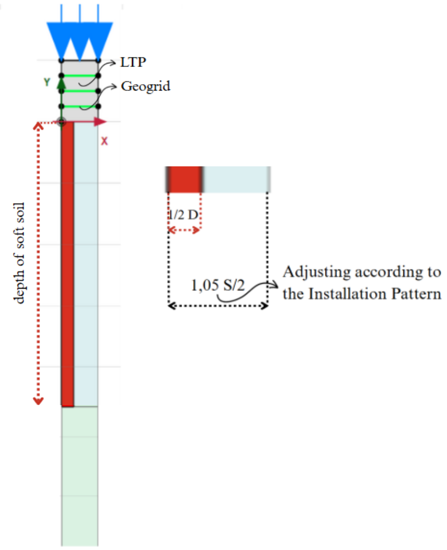

Figure 4. Domain and boundary condition

2. Geometry and Configuration of Soil Improvement

In this modeling, all soil improvement methods were applied using identical geometry specifications and configurations, including a diameter of 0.4 m, a spacing of 1 m, and an installation depth of 21.5 m (equal to the depth of the soft soil), and the configuration installation pattern used was the triangular arrangement. All llustrations of the configuration are presented in Figure 5.

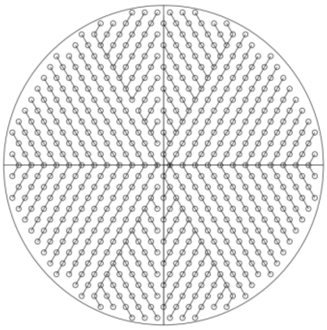

Figure 5. Soil improvement configuration

3. Material Model

All soil modeling is performed using the Mohr-Coulomb model, with input parameters obtained through the analysis of secondary data.

4. Staged Construction

The sequence of construction stages modeled includes: initial conditions, installation of stone columns, gradual installation of LTP, application of structural and service loads, and a service period followed by consolidation analysis.

IV. RESULTS AND DISCUSSION

The following shows the interpretation of the soil data, including the soil stratification, which was obtained from the collected data.

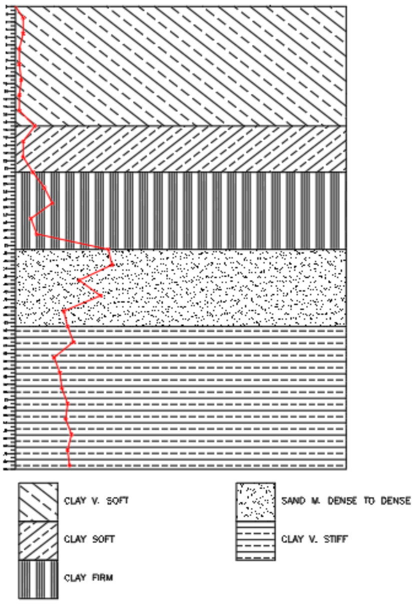

Figure 6. Stratification of soil
Source: Analysis Result

Table 1. Stratification of Soil

No	Depth			Nspt	Soil Type	Description
1	0	-	15.5	2	Clay	Very Soft
2	15.5	-	21.5	4	Clay	Soft
3	21.5	-	31.5	8	Clay	Firm
4	31.5	-	41.5	25	Sand	Med Dense
5	41.5	-	60	20	Clay	Very Stiff

Based on the previously obtained soil stratification, the design parameters were established and are summarized in the table below. These parameters, derived from a combination of field investigation data and empirical correlations from prior studies, were applied in the subsequent numerical modeling to simulate soil behavior under various improvement methods.

Table 2. Design Parameter

Layer	Depth (m)	γ_n (kN/m^3)	γ_{sat} (kN/m^3)	e0
1	0 - 15.5	12.8	14.08	1.3
2	15.5 - 21.5	13.6	14.96	1.2
3	21.5 - 31.5	15.2	16.72	1
4	31.5 - 41.5	19.25	21.175	0.8
5	41.5 - 60	16	17.6	0.6

Table 3. Design Parameter

Layer	Depth (m)	Cu (kN/m²)	C' (kN/m²)	ϕ'
1	0 - 15.5	12.8	14.08	1.3
2	15.5 - 21.5	13.6	14.96	1.2
3	21.5 - 31.5	15.2	16.72	1
4	31.5 - 41.5	19.25	21.175	0.8
5	41.5 - 60	16	17.6	0.6

Table 4. Stone Column Parameter

	Parameter	Value
Stone Columns	γunsat (kN/m²)	20
	γsat (kN/m²)	21
	Elastic Modulus (kN/m²)	38000
	Poisson's Ratio	0.33
	C' (kN/m²)	10
	ϴ' Phi (°)	38
	Kx (m/day)	1
	Ky (m/day)	0.5

Source: (Abas & Medawi, 2024)

Table 5. Geogrid Spesicification

Mechanical Properties	Units	MD Values
Tensile Strength @2% Strain	kN/m	10.5
Tensile Strength @5% Strain	kN/m	21
Ultimate Tensile Strength	kN/m	30

Source: (Biaxial Geogrid C30 Primatex)

Table 6. LTP Parameter

Model	MC	Drained
γunsat	18	kN/m²
γsat	19	kN/m²
Elastic Modulus	30000	(kN/m²)
Poisson's Ratio	0.35	[-]
C'	1	(kN/m²)
ϴ' Phi	35	(°)

Source: (Assidiqi & Prameswara, 2021)

Table 7. Kolom Grout Modular Parameter

Kolom Grout Modular	Parameter	Value
	γunsat (kN/m²)	16
	γsat (kN/m²)	22
	Elastic Modulus (kN/m²)	23500
	Poisson's Ratio	0.3
	C' (kN/m²)	85
	ϴ' Phi (°)	30
	Kx (m/day)	0.1
	Ky (m/day)	0.05

Source: (Assidiqi & Prameswara, 2021)

Table 8. Deep Soil Mixing Parameter

	Parameter	Value
Deep Soil Mixing	γunsat (kN/m²)	16
	γsat (kN/m²)	17.5
	Elastic Modulus (kN/m²)	10500
	Poisson's Ratio	0.25
	C' (kN/m²)	126
	ϴ' Phi (°)	20
	Kx (m/day)	0.1
	Ky (m/day)	0.05

Source: (Hadi, 2021)

Settlement Analysis

Based on the results of the numerical modeling, the settlements obtained for each ground improvement method are summarized in the table below.

Table 9. Summary of Settlement for Each Condition

Modeling Condition	Settlement (m)	Settlement (cm)	Settlement Reduction
Without Soil Improvement	0.5966	59.66	[-]
Stone Column	0.3176	31.76	47%
Kolom Grout Modular	0.2842	28.42	52%
Deep Soil Mixing	0.3626	36.26	39%

Table 9 above presents a summary of the settlement values that occurred under each modeling scenario, both in the existing conditions (without soil improvement) and after improvements were made using three different methods: Stone Column, Modular Grout Column (MGC), and Deep Soil Mixing (DSM).

In the existing condition, the maximum settlement observed was 0.5942 meters, or 59.42 cm. This significant settlement indicates that, without any soil improvement, the soft soil's bearing capacity is insufficient to support the applied loads, which could lead to structural instability over time. Such a level of settlement poses a serious risk to the integrity and safety of structures, making the need for effective soil improvement methods essential.

After implementing the Stone Column method, the settlement was reduced to 31.76 cm, reflecting a 47% reduction compared to the existing condition without any soil improvement. This reduction demonstrates that the Stone Column method effectively enhances the soil's bearing capacity by transferring the applied loads through relatively stiffer and more permeable stone columns, which helps in minimizing settlement and improving overall soil stability.

The Modular Grout Column (MGC) method demonstrated the most optimal performance among the three methods tested. The maximum settlement observed with MGC was 28.42 cm, showing a 52% reduction compared to the existing condition. The superior performance of MGC is likely due to the high elasticity modulus of the grout material, as well as its strong interlocking ability with the surrounding soil, which allows it to resist deformation more effectively. Furthermore, the modular geometry of the grout columns provides a more uniform and efficient load distribution path, strengthening the soft soil not only vertically but also laterally. These results indicate that MGC is a highly promising method for applications in areas with extremely soft soil characteristics, such as in the case study presented.

Meanwhile, the Deep Soil Mixing (DSM) method resulted in a maximum settlement of 36.26 cm, with a 39% reduction in settlement, which, although the largest reduction among the three methods, is still less effective compared to MGC and Stone Column. DSM's performance is somewhat limited in terms of settlement reduction.

In general, all soil improvement methods succeeded in reducing the settlement values. However, when considering settlement performance, MGC ranked highest, followed by Stone Column, and lastly DSM. This comparison provides a clear overview of the relative effectiveness of each method in the context of this case study, demonstrating that MGC offers the greatest reduction in settlement, making it the most effective method for soft soil stabilization in this scenario.

V. CONCLUSION

The results of this study demonstrate that all three soil improvement methods—Stone Column, Modular Grout Column (MGC), and Deep Soil Mixing (DSM)—effectively reduce settlement in soft soil conditions. Among these methods, MGC showed the highest performance, achieving a 52% reduction in settlement, which highlights its superior ability to enhance soil strength and distribution of loads. The Stone Column method followed closely, with a 47% reduction, proving its effectiveness in improving soil stability, though slightly less efficient than MGC. DSM, while showing the largest settlement reduction of 39%, still performed lower than the other two methods.

The comparative analysis clearly illustrates that MGC is the most effective method for reducing settlement in soft soil conditions, followed by Stone Column and DSM. These findings emphasize the importance of selecting the right soil improvement method based on specific project requirements and the characteristics of the underlying soil. The results also suggest that MGC is a promising solution for areas with extremely soft soil, offering a robust, cost-effective approach to mitigating settlement and enhancing soil stability.

For the best results, it is recommended to increase the diameter of the columns as per the specifications and availability to further enhance the effectiveness of the soil improvement method, ensuring greater load-bearing capacity and reducing settlement more efficiently.

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