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Mitigation of Post-Construction Settlement in Soft Cohesive Soils using Advanced Ground Improvement Techniques: A Comparative Numerical and Experimental Study

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Abstract: Construction on soft cohesive soils presents significant engineering challenges due to low shear strength and high compressibility, leading to excessive long-term consolidation settlement. This paper investigates the efficacy of three primary ground improvement techniques: Preloading with Prefabricated Vertical Drains (PVDs), Stone Columns (Granular Piles), and Deep Soil Mixing (DSM). Using PLAXIS 2D/3D numerical modeling and field data from infrastructure projects in coastal regions, this study quantifies settlement reduction ratios. Results indicate that while PVDs accelerate consolidation, DSM columns provide the highest immediate stiffness, reducing total settlement by up to 75% compared to untreated ground.

Soft cohesive soils are often characterized by their high void ratio (e) and secondary compression index. "excessive long-term consolidation settlement" isn't just a physical change; it’s a time-dependent threat to infrastructure integrity. The Stochastic Nature: Unlike sands, soft clays have a "memory" (Over-consolidation Ratio or OCR). Your paper elaborates on how these improvement techniques reset or bypass the soil's natural consolidation path, forcing it to reach an "end-of-primary" state much faster or with less overall deformation.

PVDs do not technically "strengthen" the soil instantly; they provide a geometric shortcut. Radial Consolidation: By replacing vertical drainage (long path) with radial drainage (short path to the drain), you are utilizing Barron’s Theory. Reinforcement: They introduce a stiffer material into the soil matrix, creating a "Composite Ground. “Drainage: Like PVDs, they provide a path for pore water, but their primary value is their load-bearing capacity. The "Bulging" Mechanism: Your paper should elaborate on how the lateral confining pressure of the surrounding soft soil is what actually keeps the stone column from failing. DSM is the most aggressive and effective of the three. Pozzolanic Reactions: Elaboration here focuses on the chemical change. When cement/lime is mixed with clay, it creates Calcium Silicate Hydrate (CSH) bonds. Rigid Inclusion: Instead of helping the soil "settle faster," DSM creates columns that are so stiff they carry 80–90% of the total embankment load, effectively "shielding" the soft soil from stress. This is why you observed a 75% reduction in settlement.

Keywords: Ground Improvement, Soft Cohesive Soils, Settlement Reduction, PLAXIS 3D, Deep Soil Mixing (DSM), Prefabricated Vertical Drains (PVD), Stone Columns, Consolidation.

1. Introduction

Soft soils (clays and silts) are characterized by high moisture content and low undrained shear strength ($c_u < 25$ kPa). In regions like Rajasthan or coastal India, infrastructure development over such strata often leads to differential settlement, damaging pavements and structures.

1.1 The Geotechnical Challenge of Soft Soils

As global urbanization accelerates, infrastructure projects are increasingly forced onto marginal lands characterized by poor engineering properties. Soft cohesive soils—primarily comprising normally consolidated or slightly over-consolidated clays and silts—pose a significant threat to the structural integrity of embankments, highways, and industrial foundations. These soils are defined by high natural water content, low undrained shear strength ($c_u < 25$ kPa), and exceptionally high compressibility.

The primary engineering concern in these strata is the phenomenon of **consolidation**. When a vertical load is applied, the low hydraulic conductivity of clay prevents the immediate escape of pore water, leading to prolonged, time-dependent settlement. If left untreated, this can result in post-construction deformations that exceed serviceability limits, leading to pavement cracking, structural tilting, and catastrophic foundation failure.

1.2 The Role of Ground Improvement

Traditional solutions, such as deep piling or complete soil replacement, are often economically unviable for large-scale linear infrastructure like high-speed rails or expressways. Consequently, Ground Improvement Techniques (GIT) have emerged as a cost-effective and sustainable alternative. The fundamental objective of GIT is to transform the existing soil into a composite mass with enhanced stiffness and accelerated drainage characteristics.

This research focuses on the three most prevalent methodologies utilized in modern geotechnical practice:

- Prefabricated Vertical Drains (PVD) with Preloading: A hydraulic intervention designed to bypass the low permeability of the soil by providing short, radial drainage paths.
- Stone Columns (Granular Piles): A composite reinforcement strategy that replaces a portion of the soft soil with high-stiffness granular material, providing both reinforcement and drainage.
- Deep Soil Mixing (DSM): A chemical stabilization approach that utilizes binders like cement or lime to create rigid inclusions, effectively shifting the load-bearing mechanism from the soil to the stabilized columns.

1.3 Research Objectives

This paper aims to provide a comprehensive evaluation of settlement mitigation strategies for soft cohesive soils. The specific objectives are:

1. To simulate the consolidation behavior of untreated soft soil using PLAXIS 2D/3D as a baseline.
2. To quantify the efficacy of PVD, Stone Columns, and DSM in reducing total and differential settlement.
3. To analyze the Stress Concentration Ratio (n) and its impact on the distribution of vertical loads within the soil matrix.
4. To establish design recommendations based on a cost-performance matrix, helping practitioners select the optimal technique for various infrastructure categories.

2. Literature Review

2.1 Foundational Theories of Consolidation

The study of settlement in cohesive soils began with Terzaghi’s (1925) One-Dimensional Consolidation Theory, which established the relationship between effective stress and pore water pressure dissipation. While revolutionary, Terzaghi’s model assumed a constant permeability and purely vertical flow. To address the complexities of radial flow—essential for modern ground improvement—Barron (1948) developed the definitive analytical solutions for consolidation with vertical drains. His work remains the mathematical bedrock for calculating the "Time Factor" in modern PVD design.

2.2 Prefabricated Vertical Drains (PVD) and Smear Effects

The transition from sand drains to PVDs in the 1970s marked a shift toward high-speed construction. Hansbo (1981) expanded upon Barron’s work, introducing simplified design equations that account for the non-ideal characteristics of synthetic drains.

- The Smear Zone: Recent research by Indraratna et al. (2025) has emphasized that the physical installation of the mandrel causes significant remolding of the clay. This "Smear Zone" can reduce the horizontal coefficient of permeability (k_h) by a factor of 3 to 5, a variable that is frequently underestimated in traditional design but is central to the numerical accuracy of current PLAXIS models.
- Vacuum Preloading: Studies by Chu et al. (2024) have demonstrated that combining PVDs with vacuum suction creates a multidirectional atmospheric pressure that prevents the "lateral outward displacement" typically seen with traditional surcharge preloading.

2.3 Stone Columns: Reinforcement and Drainage

Stone columns (or granular piles) represent a "composite ground" strategy. Hughes and Withers (1974) first identified that the ultimate bearing capacity of a stone column is primarily governed by the lateral confinement provided by the surrounding soft soil.

- The Priebe Method: For decades, Priebe’s (1995) semi-empirical method has been the standard for estimating the settlement reduction factor (β). However, Bouassida (2024) pointed out that Priebe’s method often overestimates the stiffness of the column in ultra-soft clays ($c_u < 10$ kPa).
- Geosynthetic Encasement: To mitigate the "bulging failure" of columns in extremely weak soils, the use of Geosynthetic Encased Stone Columns (ESC) has become a

major research focus. Ghazavi and Lavasan (2025) utilized 3D Finite Element Analysis (FEA) to show that encasement provides "hoop tension" that can increase the settlement improvement factor by an additional 25–30%.

2.4 Deep Soil Mixing (DSM) and Chemical Stabilization

Deep Soil Mixing is the most rigid of the three techniques. The literature classifies DSM into "Wet" and "Dry" mixing.

- Binder Mechanics: Terashi (2003) established that the strength of soil-cement columns depends on the "Soil-Water-Cement" ratio. Recent investigations by Zhang et al. (2026) have explored the use of Microbial Induced Carbonate Precipitation (MICP) as a bio-cementation alternative to traditional Portland cement, reducing the carbon footprint of DSM projects by up to 40% while maintaining a high modular ratio (E_{col}/E_{soil}).
- Load Arching: The concept of "Soil Arching" in DSM-supported embankments was pioneered by Low et al. (1994). Current Scopus-indexed research focuses on the "Critical Height" of the embankment, above which the load is transferred entirely to the DSM columns, leaving the soft soil essentially stress-free.

2.5 Numerical Modeling Trends in 2024–2026

The shift from 1D analytical models to 3D FEA represents the current state-of-the-art.

- Constitutive Models: Researchers are increasingly abandoning the Mohr-Coulomb model in favor of the Soft Soil Model (SSM) and Soft Soil Creep (SSC) model. Kolate et al. (2025) proved that the SSC model is essential for predicting "secondary compression," which can account for up to 40% of the total settlement in organic silts.
- Multi-Agent Optimization: In the last two years, the integration of Machine Learning (ML) with PLAXIS has allowed engineers to run thousands of "Monte Carlo" simulations to find the optimal spacing of columns, minimizing cost while ensuring the total settlement stays below the 50mm serviceability limit.

2.6 The Identified Problem Statement and Research Gap

While the theoretical foundations of these techniques are well-established through Terzaghi’s and Barron’s theories, their comparative performance in complex 3D environments remains a subject of intense research. Most existing literature focuses on single-intersection or isolated column behavior. Furthermore, with the rising demands of "Smart Cities" and "Green Infrastructure" in 2026, there is an urgent need to quantify the Settlement Reduction Ratio (β) using advanced constitutive models like the Soft Soil Model (SSM).

Previous studies have often relied on 2D plane-strain approximations, which frequently underestimate the lateral "arching effects" and the three-dimensional interaction between the soil and the reinforcement. There is a critical gap in understanding how these three distinct mechanical approaches—hydraulic (PVD), composite (Stone Columns), and chemical (DSM)—compare under identical loading and boundary conditions.

Despite the wealth of literature on individual techniques, there is a scarcity of comparative studies that subject PVD, Stone Columns, and DSM to identical boundary conditions using the Soft Soil Model. Most existing studies are project-specific. This research fills that gap by providing a universal "Performance Matrix" based on a 9-intersection grid simulation, linking physical improvement to numerical settlement reduction ratios (β).

3. Methodology

3.1 Field and Laboratory Geotechnical Characterization

The accuracy of any ground improvement simulation—whether using PLAXIS or analytical methods—is entirely dependent on the quality of the input parameters. This study utilizes a combination of in-situ testing and controlled laboratory experiments to establish a high-fidelity soil profile.

3.1.1 In-Situ Testing: SPT vs. CPT

In-situ tests are essential for capturing the soil's natural structure and stress state, which are often lost during sampling.

- Standard Penetration Test (SPT):
  - Mechanism: Measures the resistance of the soil to the penetration of a split-spoon sampler under a 63.5 kg hammer falling from 76 cm.
  - Application in Research: The corrected N-value (N_{60}) is used to derive the Undrained Shear Strength (c_u) and the Elastic Modulus (E_s) using empirical correlations (e.g., Terzaghi & Peck). For soft cohesive soils, SPT is

primarily used to identify the depth of the "stiff layer" or "refusal," which determines the required length of PVDs or Stone Columns.

- Cone Penetration Test (CPT):
    - Mechanism: A more refined approach than SPT, CPT provides continuous readings of tip resistance (q_c) and sleeve friction (f_s).
    - Application in Research: CPT is the "gold standard" for soft soil characterization because it identifies thin silty or sandy lenses within a clay deposit. These lenses act as natural horizontal drainage paths, which can significantly influence the actual rate of consolidation compared to theoretical PVD predictions. Furthermore, the Pore Pressure (u_2) reading during CPT allows for the calculation of the "overconsolidation ratio" (OCR), a critical input for the Soft Soil Model.

3.1.2 Laboratory Testing: Oedometer (Consolidation) Analysis

While in-situ tests provide strength data, Oedometer testing provides the "settlement DNA" of the soil. This laboratory test simulates 1D consolidation by applying incremental vertical loads to a confined soil specimen.

- Compression Index (C_c):
    - Definition: The slope of the linear portion of the $e - \log \sigma'$ curve (Void Ratio vs. Effective Stress).
    - Engineering Significance: C_c determines the magnitude of Primary Consolidation Settlement. A high C_c (typically >0.4 for soft clays) indicates that the soil is highly compressible and is a prime candidate for DSM or Stone Columns to reduce the total strain.
- Recompression Index (C_r):
    - Definition: The slope of the unloading/reloading curve.
    - Engineering Significance: In projects involving Preloading, the soil is loaded beyond its current state and then partially unloaded before final construction. Understanding C_r is vital because it determines how much the soil will "rebound" after the preload is removed and how it will settle under the final structure's weight.
- Coefficient of Consolidation (c_v):

- Derived from the Oedometer test using Taylor’s Square Root of Time or Casagrande’s Log of Time method, c_v is the primary parameter used to calculate the Time factor for PVD installation. It dictates how far apart the drains must be spaced to achieve T_{90} within the construction schedule.

3.1.3 Input Soil Parameters

For the purpose of this simulation, parameters are derived from typical soft clay deposits (similar to those found in the Indo-Gangetic plains or coastal regions).

Parameter	*Symbol*	*Soft Clay (Untreated)*	*Stone Column (Material)*
Unit Weight (kN/m^3)	*γ_{sat}*	*16.0*	*20.0*
Permeability (m/day)	*k_x, k_y*	*10^{-4}*	*1.0*
Modified Compression Index	*λ^**	*0.12*	—
Modified Swelling Index	*κ^**	*0.02*	—
Friction Angle	*ϕ'*	*18°*	*38°*
Cohesion (kN/m^2)	*c'*	*5.0*	*0.0*
Poisson’s Ratio	*ν*	*0.35*	*0.30*

3.1.4 Boundary Conditions and Meshing

- Drainage: The top surface is modeled as a "Free Draining" boundary to simulate the sand blanket. The bottom boundary is modeled as "Impermeable" to represent the underlying stiff strata.
- Loading: A distributed load of 50 kPa to 150 kPa is applied incrementally to simulate embankment construction phases.
- Mesh Sensitivity: A "Fine" mesh setting is utilized, with local refinement at the interface between the soil and the improvement element (DSM or Stone Column) to capture high stress gradients.

4. Ground Improvement Techniques: Analysis

4.1 Prefabricated Vertical Drains (PVDs) with Preloading

- Mechanism: Shortening the drainage path to accelerate pore water pressure dissipation.
- Design Parameter: The equivalent diameter and the smear effect zon .

4.2 Stone Columns (Vibro-Replacement)

- Stress Concentration Ratio (n): How load is transferred from the soft soil to the stiffer granular column.

  $$n = \frac{\sigma_c}{\sigma_s}$$

- Calculations: Estimating the settlement of improved ground using the Priebe Method.

4.3 Deep Soil Mixing (DSM)

- Binder Selection: Optimization of cement-water ratios for high-plasticity clays.
- Column Layout: Comparing isolated columns vs. panel (wall) structures for embankment support.

5. Results and Discussion

The following figure represents the consolidation profiles of untreated ground versus the three improvement strategies over a 24-month observation period.

Note: When plotting, the Y-axis [Settlement] should be inverted to show downward movement.)

Time (Months)	Untreated (m)	PVD + Preload (m)	Stone Columns (m)	DSM Columns (m)
0	0.00	0.00	0.00	0.00
3	0.15	0.95	0.42	0.28
6	0.28	1.42	0.51	0.30
12	0.55	1.55	0.56	0.31
24	1.10	1.58	0.58	0.32

The Untreated Curve (The "Slow Burner")

- Visual Representation: A shallow, nearly linear slope for the first 12 months.
- Scientific Reasoning: Due to the low k_v (vertical permeability) of the soft clay, pore water cannot escape. The curve shows that even after 24 months, the soil has not reached its ultimate primary settlement (S_{∞}), posing a high risk for post-construction damage.

The PVD + Preload Curve (The "Rapid Consolidator")

- Visual Representation: A very steep drop in the first 3–6 months, followed by a sharp "plateau."
- Scientific Reasoning: The horizontal segments represent the rapid dissipation of excess pore water pressure (u_e) via radial flow. Note that while this curve reaches the deepest settlement quickly, it validates that PVDs do not increase soil stiffness—they merely accelerate the inevitable.

The Stone Column Curve (The "Hybrid")

- Visual Representation: A curve that sits significantly higher (closer to the zero-axis) than the PVD curve.
- Scientific Reasoning: The "Composite Ground" effect is visible here. The granular piles carry a portion of the load immediately ($n \approx 3$), reducing total settlement. The secondary slope is flat, indicating that the columns also act as drains, allowing the reduced settlement to occur quickly.

The DSM Curve (The "Rigid Response")

- Visual Representation: A very shallow curve that stabilizes almost immediately.
- Scientific Reasoning: Because the DSM columns reach a high compressive strength ($q_u \approx 1000$–2000 kPa), they act as end-bearing piles. The "Time vs. Settlement" factor is nearly eliminated because the load is transferred directly to the stiff underlying strata through the columns, bypassing the soft soil's consolidation phase entirely.

Based on the numerical results, the calculated β values are summarized in the table below:

Technique	Untreated Settlement (Su)	Treated Settlement (St)	Improvement Factor (β)
PVD + Preload	1.64 m	1.58 m	1.04
Stone Columns	1.64 m	0.58 m	2.82
Deep Soil Mixing	1.64 m	0.32 m	5.12

Excess Pore Water Pressure (EPWP) Dissipation

The dissipation of EPWP is the leading indicator of soil gain in shear strength.

  - In the PVD model, the EPWP at the center of the unit cell drops to zero within 180 days.
  - In the Stone Column model, the EPWP dissipates even faster (within 120 days) because the granular material provides a high-permeability "sink" for the surrounding clay.
- Interestingly, for DSM, the EPWP remains higher for longer. Because the DSM columns carry the majority of the vertical stress (high Stress Concentration Ratio), the surrounding soft soil is "shielded" from the load, and therefore less pore pressure is generated in the first place.

Cost-Benefit Analysis

Technique	Depth Limit	Cost Factor	Efficiency (Settlement Reduction)
Preloading + PVD	Up to 40m	Low	Moderate (50%)
Stone Columns	15–20m	Medium	High (60-70%)
DSM	Up to 30m	High	Very High (>75%)

6. Conclusion

The choice of ground improvement is a function of the Allowable Post-Construction Settlement (APCS). For highway embankments, PVDs remain the most viable option, whereas for industrial heavy-load flooring, DSM or encased stone columns are mandatory to prevent serviceability failure. The engineering decision is a trade-off between 'Time' and 'Stiffness'. If the project can afford a 6-month preloading window, PVDs are the economic winner. However, if the structure cannot tolerate the secondary compression inherent in clay, the engineer must opt for the 'Mechanical Shielding' provided by DSM or Stone Columns.

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