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A Comprehensive Review of Column-Based Ground Improvement Techniques: Mechanisms, Design, and Field Applications

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Abstract

This paper offers a comprehensive review of column-based ground improvement techniques, focusing on their fundamental mechanisms, design principles, construction methods, and field applications. It highlights stone columns and deep soil mixing (DSM) as the most widely used and effective solutions for enhancing the performance of weak and compressible soils. The core principles, including stress redistribution, increased shear strength, and accelerated consolidation, are discussed in detail. The review synthesizes key design parameters such as column geometry, area replacement ratio, and the role of geosynthetic reinforcement and load transfer platforms. It also examines the practical application of these methods through various case studies on embankments, tank foundations, and excavation supports. A dedicated section explores the pivotal role of numerical modeling, especially the finite element method (FEM), and emerging AI-driven approaches like Physics-Informed Neural Networks (PINNs) and surrogate modeling, which are shown to improve predictive accuracy and optimize the design process. Furthermore, the paper addresses critical challenges and limitations, including material variability, installation uncertainties, environmental impacts, and the need for enhanced quality control and long-term monitoring. It concludes by outlining future trends and innovations, such as the adoption of sustainable materials and the integration of machine learning for predictive design and real-time monitoring. This synthesis provides a structured overview of current best practices and offers valuable insights into the future direction of this vital area of geotechnical engineering.

Keywords: Ground Improvement, Column-Based Techniques, Stone Columns, Deep Soil Mixing, Numerical Modeling, Finite Element Method (FEM), Settlement Control.

I. Introduction

Weak or compressible soil conditions pose significant challenges to the safe and economical design of infrastructure such as embankments, buildings, tanks, and transportation systems. In geotechnical engineering, ground improvement techniques are essential solutions used to enhance soil properties and ensure structural performance. Among the diverse range of available methods, column-based ground improvement techniques have emerged as some of the most efficient and widely implemented approaches. These methods involve the insertion of stiffer elements-such as stone columns, sand compacted columns, or deep soil mixing columns—into soft ground to improve bearing capacity, control settlement, and enhance stability.

The fundamental concept of column-based improvement is to replace or reinforce weak soils by creating a composite system in which the installed columns carry a greater portion of the applied load. This process results in a redistribution of stresses, often accompanied by beneficial effects such as the arching phenomenon and reduction in pore water pressures. As a result, these techniques are commonly used in soft clay deposits, loose sands, and organic soils, where traditional shallow or deep foundation systems may not be feasible or cost-effective.

The design of columnar systems depends on several factors, including the type and properties of the columns, area replacement ratio, installation patterns, and the use of load transfer platforms or geosynthetic reinforcements. Moreover, advancements in numerical modeling-particularly with finite element methods—have improved the ability to predict performance, optimize designs, and compare various installation strategies under different loading and boundary conditions.

This paper presents a comprehensive review of column-based ground improvement techniques, focusing on their mechanisms, design principles, construction methods, and field applications. The objective is to provide a detailed and structured synthesis of the current state-of-practice and to highlight key challenges, innovations, and future directions in this vital area of geotechnical engineering.

II. Classification and Mechanisms of Column Based Ground Improvement

Column based ground improvement techniques can be broadly classified into granular (e.g. stone columns, vibro replacement), displacement (rammed aggregate piers), and cementitious (e.g. deep soil mixing, cemented stone columns). These methods enhance soil strength and stiffness by creating a composite ground system through load redistribution, stress concentration, and accelerated consolidation.

Recent literature emphasizes the performance of stone columns in improving soft soils. A comprehensive review by Kumar & Kumar (2023) [1] examines stone column effectiveness in bearing capacity and failure modes, based on field data and numerical simulations from 2000-2021. Basack et al. (2023) [2] conducted a combined field and advanced numerical study on load-settlement behavior of stone columns, demonstrating high predictive accuracy when validated with field measurements. Abas et al. (2024) [3] investigated stone columns in sabkha soil for tower foundations in Saudi Arabia, showing improved bearing capacity and reduced settlement under vibro replacement wet top feed method. Ghazavi et al. (2024) [4] assessed analytical models for predicting stone column bearing capacity and highlighted limitations of classical methods In another innovation, cemented stone columns were explored, revealing significantly improved performance compared to granular-only columns.

Cementitious column methods such as deep soil mixing (DSM) and deep cement mixing (DCM) remain widely used. Coventry University's review (2019) [5] summarized strengths, limitations, and performance variability in cement based columns across soft soil environments. Hong Kong and Tokyo infrastructure projects apply DCM extensively, combining wet and dry mixing techniques optimized in recent decades. More recent research explores hybrid methods such as stone columns injected with cementitious grout containing nanoparticles (e.g. CNT/cement meta models) to enhance stiffness and sustainability.

Numerical and mechanistic studies emphasize load transfer mechanisms-especially arching effects, area replacement ratio (AS), and stress redistribution. Ghorbani et al. (2021) [6] performed 2D FEM simulations to study stone columns combined with basal geosynthetics beneath embankments, showing enhanced deformation control and increased stability. Yao et al. (2025) [7] proposed optimized T shaped soil–cement deep mixing column configurations that improve performance under different loading scenarios, emphasizing sustainability.

The growing interest in reliability-based design approaches is evidenced by Ghazavi et al. (2025) [8], integrating probability-based assessments for stone column design to better account for variability and uncertainty in field performance.

In summary, recent studies since 2019 collectively expand our understanding of column types, installation methods, and mechanisms-while evaluating improvements in bearing capacity, settlement control, and structural reliability.

III. Design Considerations

Designing effective column based ground improvement systems requires rigorous evaluation of key parameters: column diameter, length, spacing, grid pattern, area replacement ratio (AS), and the use of encasement or load transfer platforms. Optimal performance depends on tailoring these parameters to soil conditions, loading scenarios, and cost constraints.

Recent optimization studies by Nguyen et al. (2022) [10] applied multi objective algorithms to determine optimal column diameter, length, and spacing that minimize cost while meeting design criteria. In slope stability contexts, Peng et al. (2024) [11] demonstrated that (AS) significantly influences factor of safety, and identified thresholds ($\approx$ 24.6%) beyond which additional material offers diminishing returns.

Column spacing guidelines typically range between 2–3 m center to center depending on soil type and load requirements, with minimum spacing of about 1.5 × column diameter for smaller footing groups. Pourakbar et al. (2023) [12] reported typical DSM column spacing of 1.0–1.5 m, with diameters from 0.5 to 1.75 m depending on strength requirements.

Area replacement ratio (As) is widely recognized as a dominant design variable. Miranda (2021) [13] varied AS over 10–100%, finding clear nonlinear relationships between AS and bearing capacity/stiffness of composite ground. Design recommendations emphasize (AS) selection to balance settlement reduction and cost effectiveness.

Parameters influencing DSM design include injection pressure, cement dosage, and mixing time-which affect unconfined compressive strength (UCS). Inanç Onur et al. (2022) [14] found that these factors interact strongly and must be adjusted based on native soil properties to achieve target UCS values. Abas et al. (2024) [15] further simulated DSM excavation support in sabkha soils-highlighting depth constraints and anchoring requirements in design models.

Simplified assumption based methods still play a role: Sun et al. (2024) [16] reviewed consolidation behavior in high AS conditions, showing enhanced drainage and accelerated settlement when AS exceeds ~35%. Meanwhile, academic comparisons (Einarsson & Persson, 2024) [17] using unit cell analysis in Plaxis 2D confirmed that DSM generally yields slightly better settlement control than stone columns when using similar AS and spacing.

Together, these studies underline the importance of structured parameter selection: balancing AS, column geometry, and binder strength to achieve reliable performance at minimum cost and within geotechnical limitations.

IV. Construction Techniques and Load Transfer Platforms

Construction methodologies and appropriate load transfer platform (LTP) design are critical for realizing the intended performance of column based ground improvement systems. Successful installation depends on equipment precision, quality control, and integration with reinforcement systems [18].

A. Vibro Replacement & Aggregate Piers

Stone columns are typically installed using vibro replacement techniques, either wet top feed or dry bottom feed, to densify and replace weak soil layers. Appropriate spacing and diameter selection are essential to avoid excessive displacement or column bulging during installation [19]. Geosynthetic encasement around stone columns (GESCs) significantly enhances lateral confinement, reduces bulging, and improves settlement behavior; especially effective for non-uniform column geometry and floating foundations in soft clay [20].

B. Deep Soil / Cement Mixing (DSM/DCM)

Cementitious columns involve mixing soil in situ with binder agents (e.g. cement or lime) using rotating augers or mixing blades. Injection pressure, mixing duration, and binder dosage directly influence unconfined compressive strength and column homogeneity [21].

C. Load Transfer Platforms (LTPs)

To amplify load sharing and reduce the number of columns required, geosynthetically reinforced LTPs are installed between the column heads and overlying fill. These act like rigid beam or membrane systems to transfer loads across columns and induce soil arching [22].

V. Applications in Field Practice

Real-world applications of column based ground improvement illustrate the effectiveness and diversity of deployment in challenging soft ground conditions across various infrastructure projects. The following key case studies and applications from the literature since 2015 demonstrate how these techniques perform in practice.

A. Embankment Support and Settlement Control

Wassie and Demir (2023) analyzed an embankment over stone column–reinforced soft soil using PLAXIS 2D modeling, demonstrating settlement reductions from approximately 54 mm to 33 mm as the area replacement ratio increased from 10% to 20%, and emphasizing the stabilizing effect of basal geosynthetics [23]. Similarly, Ghorbani et al. (2021) [24] investigated embankment behavior with granular columns and reinforcement, reporting improved stability and accelerated consolidation beneath embankments. More recently, Tan et al. (2025) [25] numerically modeled geotextile-wrapped stone columns, revealing further suppression of lateral bulging and enhanced load-bearing capacity, particularly for high-fill embankments in soft clays.

B. Deep Soil Mixing for Infrastructure Support

Moradi et al. (2023) [26] evaluated deep soil mixing (DSM) columns installed beneath circular liquid tanks, finding that the columns significantly reduced settlement and enhanced foundation performance. Abas et al. (2024) [27] conducted finite-element simulations of DSM walls for excavation support in sabkha soils, confirming DSM as an effective solution for controlling lateral displacements in coastal and arid environments. Similarly, Pan et al. (2022) [28] applied DSM reinforcement to mitigate the effects of adjacent construction on shield tunnels in soft ground, demonstrating effective control of ground movement and tunnel deformation.

C. Mass Soil or Mixing Programs

Amer et al. (2024) [29] reported a mass soil mixing field trial in Egypt that integrated groundwater control objectives and achieved significant improvements in the strength and permeability characteristics of soft clays. Similarly, a case study in Eskisehir, Turkey [30], described DSM installation for the foundation of an eight-story hotel, where field core analyses and load testing confirmed substantial enhancement of bearing capacity, even in highly compressible soils.

D. Geosynthetic Encased Stone Column Applications

Selma et al. (2024) [31] employed advanced 3D modeling to optimize geosynthetic encasement reinforcement for stone columns beneath embankments, demonstrating significant benefits in settlement reduction and lateral stability control. Likewise, Harelimana et al. (2022) [32] experimentally investigated geosynthetic-encased stone columns in extremely soft clay, reporting improved load response and reduced deformation compared to non-encased columns.

VI. Numerical Modeling and Analysis

Numerical simulations-especially finite element analyses (FEA)-play a pivotal role in understanding and designing column-based ground improvement systems. These models help capture load transfer, stress redistribution, consolidation, and failure mechanisms more accurately than empirical solutions.

A. Modeling Strategies for Stone Columns

J. Castro's fundamental review (2017) [33] outlines several geometrical modeling approaches: unit-cell, plane-strain trenches, cylindrical rings, equivalent homogenization, and 3D slice models. It also defines the concept of critical column length-typically about twice the footing width in soft clay-and its influence on results.

Recent reviews by Teshager et al. (2022) [34] highlight best practices in FEM modeling, noting key parameters such as mesh density, constitutive models, and column–soil interface treatment.

Tan et al. (2025) [35] conducted 3D Plaxis modeling to investigate vertically and horizontally reinforced stone columns, confirming that dual-direction geosynthetic layers substantially improve bearing capacity and mitigate bulging; their numerical results matched laboratory tests closely. Saxena & Roy (2022) [36] presented parametric PLAXIS simulations comparing pebble gravel and crushed gravel columns, emphasizing L/D ratio effects, bulging, and soil stiffness variations.

B. Modeling Deep Soil Mixing Columns

Moradi et al. (2023) applied DSM columns beneath storage tanks and modeled behavior using coupled mechanical and hydraulic parameters in Plaxis, showing strong correlation between field observations and simulation outputs. Fulambarkar et al. (2025) [37] analyzed DMM (deep mixing method) using numerical simulations to assess the impact of column layout and depth on settlement reduction in soft ground.

C. Coupled Consolidation and Load Transfer Effects

Abdelbaset et al. (2023) [38] performed extensive numerical consolidation studies under stone columns with varying AS and length, highlighting optimum parameter ranges to reduce postconstruction settlement.
Ghorbani et al. (2021) simulated embankment deformation with basal reinforcement, demonstrating that stone columns notably enhance stability and accelerate consolidation beneath embankments.

D. Emerging Techniques: AI-Enhanced Modeling
Physics Informed Neural Networks (PINNs) have recently been applied to solve complex three-dimensional consolidation PDEs with over 99 % accuracy compared to traditional models, offering rapid processing for settlement predictions [39]. Rodríguez Romero et al. (2023) [40] introduced hierarchical meta modeling for elastic properties prediction of CNT/cement injected stone columns-delivering efficient yet accurate surrogate models for large scale analyses.

VII. Challenges and Limitations
Although column-based ground improvement techniques offer significant advantages in many geotechnical scenarios, several inherent challenges and limitations can impact their effectiveness and applicability. Understanding these issues is essential for realistic project design, implementation, and risk assessment.

A. Material and Installation Uncertainties
Variability in native soil stratigraphy and column material properties (e.g., grading, binder quality) can cause notable differences between design predictions and actual performance. Bagheri and Najafi (2023) [41] reported that stone column behavior is significantly influenced by inconsistent refusal criteria during installation. In cementitious columns formed by DSM/DCM, homogeneity is highly dependent on mixing speed, binder ratio, and moisture content, with dilation blocks and void formation being common issues, particularly in soils with high water content (Li et al., 2024) [42].

B. Geometrical and Spacing Constraints
Achieving an optimal area replacement ratio (AS) can be challenging in dense urban environments or where underground utilities restrict allowable spacing or layout, with oversized columns potentially causing bulging during installation in soft soils (Kumbhar & Reddy, 2022) [43]. Furthermore, mismatches between column diameter and length and the actual soil layering may result in treatment zones that do not extend below active consolidation zones, thereby limiting the effectiveness of settlement reduction (Zhu et al., 2023) [44].

C. Environmental and Sustainability Concerns
Cement use in DSM and stabilized stone columns contributes substantially to carbon emissions, and while recent research into eco-friendly binders—such as alkali-activated materials—shows promise, these alternatives are not yet widely implemented in field practice (El Shimi et al., 2024) [45]. Additionally, the disposal of spoil and effluent generated during vibratory stone column installation, particularly in saturated clays, poses significant logistical and environmental challenges (Sharma & Gupta, 2023) [46].

D. Cost and Practical Constraints
High initial capital costs—especially for DSM installations with high binder content—can limit their feasibility for routine applications in developing regions (Mwangi et al., 2023) [47]. Moreover, long-term performance monitoring for settlement and lateral bulging is often excluded from project budgets, reducing the availability of empirical data needed to refine design models (Singh & Park, 2022) [48].
7.5 Performance Monitoring and Quality Assurance
In-situ validation remains limited. Only a few case studies (e.g. Han et al., 2021) [49] provide comprehensive pre and post installation instrumentation. Lack of standardized QA/QC protocols can result in underperformance (UCS values below target, misalignment).

VIII. Future Trends and Innovations
Emerging innovations are reshaping the development, design, and implementation of column-based ground improvement methods. These trends are increasingly driven by sustainability considerations, digital technologies, and machine learning integration to enhance efficiency, predictive accuracy, and environmental performance.

A. Sustainable and Green Materials
In response to rising concerns over carbon emissions associated with cement-based columns, recent studies are exploring geopolymer or fly-ash-based binders as sustainable alternatives. Saride et al. (2024) [50] demonstrate that geopolymer DSM columns, using fly ash, effectively reduce swelling and shrinkage whilst enhancing soil stiffness. Mach & Wałach (2024) [51] conducted a bibliometric review revealing significant research gaps in life cycle sustainability assessment of ground improvement techniques, emphasizing environmental and economic metrics in design selection.

B Integration of Life Cycle Assessment
There is growing advocacy for integrated life cycle design frameworks to evaluate environmental impacts, vibration and noise, cost, and construction time efficiency holistically. Mach & Wałach (2024) underscore the need for multi-criteria decision-making tools to compare DSM, stone columns, and hybrid systems in sustainability-sensitive scenarios.

C. AI-Driven Predictive Design and Quality Monitoring
Machine learning is increasingly integrated into design workflows and quality control. Liu et al. (2024) [52] review AI methodologies in computational geomechanics, outlining common usage of ANN, SVM, and RF to predict mechanical parameters with improved fidelity. Saad et al. (2023) [53] provide a systematic review of ML for soil improvement using green materials, noting their efficacy in predicting compressive strength, bearing capacity, and settlement behavior.
Specifically for ground treatment, Terbuch et al. (2022) [54] implemented a hybrid ML-based quality control system for vibro stone column installations, improving detection of incomplete installation or bulging during placement.

D. Surrogate and Meta Modeling Approaches
Surrogate modeling techniques, such as Physics-Informed Neural Networks (PINNs) and meta-models, are gaining traction for rapid simulation of stress–strain and

consolidation behavior in complex ground systems. Yuan et al. (2024) [55] demonstrate PINNs achieving ~99% accuracy in predicting 3D consolidation PDEs. Rodríguez Romero et al. (2023) [56] develop hierarchical meta-models specific to CNT-incorporated cement-stabilized columns, highlighting speed and scalability advantages.

E. Big Data Analytics and Multiphysics Integration

T. Zhao et al. (2024) [57] review ML techniques for predicting geotechnical parameters, underscoring the shift toward big-data driven modeling in soil improvement and material performance. In addition, Aminpour et al. (2022) [58] integrate ML with Monte Carlo simulations to perform efficient reliability analysis for slope-stability problems—principles applicable to probabilistic design of column systems.

F. Real-Time Monitoring & Smart Sensing

While this area remains nascent, the use of embedded sensors (e.g., fiber optics, IoT accelerometers) combined with ML algorithms for real-time monitoring of column deformation, settlement, and consolidation is emerging. These systems support ongoing performance assessment, risk detection, and adaptive maintenance strategies.[59].

IX. Conclusions

This review has synthesized the current state-of-practice, research advancements, and emerging innovations in column-based ground improvement techniques, with a focus on stone columns, deep soil mixing (DSM), and related hybrid systems. Across diverse applications-ranging from embankment stabilization and tank foundation support to excavation protection-these methods have consistently demonstrated their capacity to enhance load-bearing performance, reduce settlement, and improve overall stability in weak and compressible soils. The collective body of research confirms that the effectiveness of these systems is governed by a complex interaction of design parameters, including column geometry, spacing, area replacement ratio, material quality, and the incorporation of reinforcement measures such as geosynthetic encasement and load transfer platforms. Numerical modeling, particularly using finite element methods, has emerged as an indispensable tool for understanding load transfer mechanisms, optimizing designs, and evaluating performance under varying soil and loading conditions. Furthermore, recent advances in AI-driven approaches, surrogate modeling, and physics-informed neural networks have shown promise in improving predictive accuracy, reducing computational demand, and supporting real-time decision-making.

Despite these advancements, several challenges remain. Material variability, installation uncertainties, and geometric constraints can hinder performance, while environmental concerns-particularly the carbon footprint of cement-based binders and spoil management-demand the development and field adoption of more sustainable solutions. Cost limitations and the frequent omission of long-term monitoring in project planning further restrict opportunities for empirical data collection and refinement of design methodologies. Addressing these issues will require integrated strategies that combine rigorous quality assurance protocols, life-cycle assessment frameworks, and innovative material technologies.

Looking ahead, the trajectory of column-based ground improvement is moving toward sustainability, digitalization, and data-driven optimization. The integration of eco-friendly binders, AI-enabled predictive design, smart sensing systems, and big-data analytics holds the potential to transform both design and construction practices. As geotechnical challenges grow more complex with urban densification, climate change impacts, and the demand for resilient infrastructure, column-based techniques-grounded in robust engineering principles and augmented by technological innovation-will remain a critical component of sustainable ground engineering. The continued convergence of field experience, experimental research, and computational advances will not only enhance performance reliability but also expand the boundaries of applicability for these versatile ground improvement methods.

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