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Review Article

Embankment Resting on Problematic Soil: A Critical Review

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Abstract *- Rapid infrastructure expansion, including high-speed railroads, freight corridors, and highways, has led to extensive construction activities across both rural and urban regions. This growth poses a significant challenge for researchers and engineers worldwide, who continuously seek innovative solutions to enhance weak soils, ensuring they meet the demands of various engineering structures. The stability of embankment foundations, particularly when built on soft soil masses, is often compromised due to the inherent characteristics of such soils, including high compressibility, plasticity, sensitivity, low shear strength, and poor permeability. This paper provides a comprehensive review of the challenges encountered during the construction of embankments on soft ground and offers recommendations for effective remedial measures. This review highlights critical considerations such as settlement, slope stability, and soil bearing capacity by analyzing the various factors that influence embankment stability through a systematic approach that incorporates past experimental and numerical studies. Common ground improvement techniques have been identified as effective solutions, such as preloading combined with Prefabricated Vertical Drains (PVD) and using lightweight fill materials. The insights gained from this study can assist engineers and consultants in developing design strategies and innovative solutions to address the challenges posed by land scarcity and problematic soils.*

Keywords – *Embankment, Soft soil, Prefabricated vertical drain, Settlement, Stability.*

1. Introduction

The rapid expansion of infrastructure across the globe has necessitated extensive construction activities, particularly in developing transportation networks such as highways, railroads, and freight corridors. These developments are crucial for economic growth, enhancing connectivity between urban and rural areas and facilitating the efficient movement of goods and people. However, one of the most significant challenges encountered in these large-scale construction projects is the variability of soil conditions, particularly the prevalence of problematic soils. Problematic soils, characterized by low bearing capacity, high compressibility, and poor shear strength, pose a substantial risk to the stability and longevity of embankments, which are critical components of transportation infrastructure [1]. Soft soils, including clays, silts, and peats, are commonly found in many parts of the world, especially in regions with high water tables or coastal areas [2]. These soils are notorious for their poor engineering properties, which can lead to excessive settlement, slope instability, and, ultimately, the failure of the constructed embankments [3]. As urbanization and infrastructure development continue encroaching upon areas with these challenging soil conditions, innovative and effective ground improvement techniques are becoming increasingly imperative [4]. The construction of embankments on soft soils requires careful consideration of various factors, including the soil's load-bearing capacity, settlement behavior, and the potential for lateral deformations [5]. Traditional construction techniques, which might be suitable for stable soils, often prove inadequate when applied to soft soils. As a result, engineers and researchers have developed a range of ground improvement methods designed to enhance the properties of these soils, making them more suitable for supporting large-scale infrastructure projects [6].

Ground improvement techniques can be broadly categorized into mechanical, hydraulic, chemical, and the use of reinforcement materials. Each method has its advantages and limitations, depending on the specific soil conditions and the construction project requirements [7]. For example, preloading combined with Prefabricated Vertical Drains (PVD) is a widely used method that accelerates soil consolidation, thereby reducing post-construction settlement [8]. Similarly, incorporating lightweight fill materials can decrease the load on the soft soil, mitigating the risk of excessive settlement and instability [9]. The importance of selecting appropriate ground improvement techniques cannot be overstated, as the consequences of failure in embankment construction can be catastrophic [10]. Infrastructure failures not only lead to significant economic losses due to repair costs and service disruptions but can also result in loss of life. Therefore, thorough investigation, careful planning, and the application of proven engineering practices are paramount in ensuring the success of embankment projects on problematic soils [11].

1.1. Problematic Soils

Problematic soils refer to those with unfavorable geotechnical properties that hinder their use as construction foundations without improvement. These include expansive clays prone to swelling and shrinkage, high-plasticity silts susceptible to deformation, and highly compressible organic-rich peats. In contrast to standard soils, these types exhibit low bearing capacity, excessive settlement potential, and poor permeability, necessitating advanced ground improvement techniques.

1.2. Research Gap

Although numerous studies have investigated embankment stability and soil improvement techniques, a comprehensive understanding of the interplay between ground improvement methods and site-specific soil conditions remains elusive. Additionally, most research has focused on settlement reduction, with limited attention given to lateral deformations and the combined effects of seismic activities and rainfall on embankment stability. Furthermore, detailed evaluations of modern reinforcement materials, such as advanced geosynthetics, are lacking under varying environmental and loading conditions.

1.3. Objective

This paper aims to address these gaps by critically reviewing embankment construction challenges on soft soils and the efficacy of various remedial measures. Through an analysis of experimental and numerical studies, the paper highlights innovative solutions and offers insights into best practices for mitigating risks associated with embankments on soft ground. The findings will assist engineers and consultants in developing tailored design strategies for sustainable and resilient infrastructure development.

This study's novelty is its integration of experimental and numerical findings to provide a holistic understanding of ground improvement techniques for embankments on soft soils. Unlike prior reviews, this paper emphasizes underexplored areas such as lateral deformations, multi-hazard scenarios, and the use of advanced materials in ground improvement. This review paper aims to comprehensively analyse the challenges associated with embankment construction on problematic soils and the various techniques developed to address these challenges. By critically examining past experimental and numerical studies, this paper offers valuable insights into the effectiveness of different ground improvement methods and their applicability in various soil conditions [12, 13].

In summary, the increasing demand for infrastructure development in areas with challenging soil conditions necessitates a deep understanding of the behavior of problematic soils and the implementation of effective ground improvement techniques. This review aims to consolidate current knowledge in the field, providing engineers and researchers with a valuable resource for improving the design and construction of embankments on soft soils, ultimately contributing to the safety and sustainability of infrastructure projects worldwide.

2. Literature Review

The history of civil engineering is closely linked to foundational work on low-bearing-capacity soils, especially with regard to adapting to the challenges posed by soft soils. Embankments constructed on such soft ground—commonly used for roadway corridors, railroad tracks, and airstrips—are often prone to edge stability issues and long-term settlement. Soft soils, typically consisting of fine-grained materials like silt, clay, and peat, are characterized by high moisture content and are generally found near or below the groundwater table. Key features of these soils include high compressibility, plasticity, sensitivity, low shear strength, and low permeability. Due to these characteristics, significant settlement and limited bearing capacity become critical factors to consider both during and after the construction of any civil engineering project.

Karl Terzaghi (1925) was the first to investigate the behavior of soft soil settlement. He defined total settlement as the overall downward movement of a structure, while differential settlement refers to the relative vertical movement between two points. The total settlement consists of elastic deformation, consolidation, and creep. The study of embankments resting on soft soils, along with the associated remedial measures, has been explored through both experimental and numerical investigations.

Studies included in this review were selected based on their focus on ground improvement techniques for soft soils, published within the last two decades. Priority was given to peer-reviewed articles employing experimental, numerical, or hybrid methodologies. Criteria such as innovation in technique, practical applications, and reproducibility of findings were also considered to ensure the inclusion of impactful research. Case studies, such as the application of PVDs in the Bangkok Clay region and the use of geogrid-reinforced embankments for the Kolkata Metro, demonstrate the efficacy of these methods in mitigating settlement and enhancing stability. Comparative analyses of these cases with global benchmarks underscore regional variations in technique effectiveness.

2.1. Experimental Investigation

Sharma and Bolton [2] employed centrifuge modeling to study the behavior of reinforced embankments on soft clay. Their findings suggest that surface-applied geogrids may not be sufficient for stabilization due to weak adhesion between the reinforcement and the clay. Redana [3] investigated the performance of two embankments constructed on soft clay and subjected to vertical drain installation. This study considered the smear effect around Mandrel-driven drains, significantly influencing settlement behavior. By utilizing the Biot-consolidation and modified Cam-clay models, the study simulated the consolidation process of the soft clay.

Rowe and Li [4] examined geosynthetic-reinforced embankments on various soil types, focusing on the influence of reinforcement and soil properties on embankment behavior. They highlighted the benefits of Prefabricated Vertical Drains (PVDs) and reinforcement tension in enhancing stability. Madhavi Latha et al. [5] proposed a simplified design approach for geocell-supported embankments, demonstrating their effectiveness in improving load-bearing capacity and reducing deformations. For a high-speed rail project, Arulrajah et al. [6] investigated ground improvement techniques, including Vibro-replacement, deep soil mixing, and geogrid-reinforced piled embankments. They concluded that Vibro-replacement is effective across various soil types, while other techniques like piled embankments and exclusion operations were also considered.

Sinha et al. [7] developed a novel approach to accelerate high embankment construction by utilizing in-situ soil strength and accelerating consolidation. Choudhary et al. [8] conducted laboratory model analyses to assess the bearing capacity of footings on geogrid-reinforced fly ash slopes, considering factors like geogrid location, number of layers, and footing position. They found that reinforcement significantly improved both pressure-settlement behavior and ultimate bearing capacity.

Zhou et al. [9] employed an organic polymer soil stabilizer, ADNB, to stabilize a clayey slope, improving soil stability and erosion resistance. López-Acosta et al. [10] investigated drain-to-drain vacuum preloading for a test embankment, finding that vacuum preloading and longer drains enhanced consolidation rates and reduced lateral movement. Pham [11] introduced a novel theory that integrates arching and tensioned membrane theories, considering subsoil effects and linear and non-linear models, providing a more comprehensive design method. Chen et al. [12] evaluated the performance of geosynthetic-encased stone column (GESC)-reinforced embankments on soft clay through centrifuge model tests, demonstrating reduced settlement and improved stress concentration ratio. Kumar and Samanta [13] conducted practical investigations to assess the time-dependent behavior and peak stress concentration ratio of stone columns, finding that the top sand blanket significantly influenced the SCR.

In summary, it provides valuable insights into embankment stability and soil improvement. Key learnings include the limitations of geogrid reinforcement due to poor soil adhesion, the significant impact of vertical drains on settlement in soft clay, and the enhanced stability provided by geosynthetic reinforcements. Additionally, the effectiveness of geocell-supported embankments in improving load-bearing capacity and reducing deformation has been highlighted, alongside the efficacy of ground improvement methods like Vibro-replacement and deep soil mixing. These findings collectively underscore the importance of innovative materials and techniques in addressing challenges associated with embankment stability and soft soil environments.

2.2. Numerical Investigation

El Sawwaf et al. [14] demonstrated the benefits of reinforcing a replacement sand layer near a sloping crest through numerical modeling and experimental validation. Geogrid layers were found to increase footing strength and reduce the required depth of reinforced sand. Optimal geogrid parameters were also identified. Madhavi Latha et al. [15] conducted a parametric finite element analysis of geocell-supported embankments, showing that increasing geocell layer depth enhanced soil strength and stiffness. Deb et al. [16] developed a mechanical model to analyze geosynthetic-reinforced granular fill over soft soil, demonstrating good agreement with experimental results. Zheng et al. [17] compared the performance of unreinforced, geosynthetic-reinforced, and geosynthetic-pile wall-reinforced embankments on soft ground, concluding that both pile walls and geosynthetic layers significantly improved soft ground conditions.

Magnani et al. [18] analyzed two trial embankments on soft clay, correlating factors like embankment load, safety factors, reinforcement forces, and inclinometer readings with critical failure surfaces. Zhang et al. [19] proposed a simplified method for evaluating geocell-supported embankments, considering vertical stress dispersion and reinforcement effects. The study highlighted the importance of geocell placement on crushed stone cushions for enhanced bearing capacity.

Rowe et al. [20] investigated the combined viscoplastic behavior of foundation soil and viscoelastic reinforcement under working stress conditions, developing a limit equilibrium-based design approach. Factors like undrained shear strength, reinforcement stiffness, and soil viscosity were identified as crucial for embankment performance. Sitharam et al. [21] demonstrated the effectiveness of combined geocell and geogrid reinforcement in enhancing the performance of embankments on soft clay.

Khan and Abbas [22] analyzed the seismic stability of a highway embankment on soft soil using fly ash fill and geogrid reinforcement. Numerical modeling using PLAXIS 2D revealed minimal displacement in critical areas. Bhatnagar et al. [23] assessed embankment-foundation dynamics and liquefaction countermeasures using PLAXIS 3D, showing that stone columns effectively reduced excess pore water pressure and displacement. Grimstad et al. [24] explored the impact of pore pressure and creep on lateral soil deformations, demonstrating increased settlement, pore pressure, and lateral displacement under seismic loads with increasing creep rates. Smith et al. [25] used the Discontinuity Layout Optimization (DLO) approach to evaluate reinforced and unreinforced embankments, establishing a design envelope linking soft soil and reinforcement strength to overall stability.

Klai and Bouassida [26] developed a constitutive law for Tunis soft clay and used PLAXIS 2D to simulate embankment construction, emphasizing the importance of ground improvement techniques. Sitharam et al. [21] compared the performance of different 3D-cellular confinement systems for reinforcing soft clay floors, finding that bamboo cells offered the highest bearing capacity due to their advanced stiffness, tensile strength, and surface roughness. Nujid and Taha [27] used COMSOL Multiphysics to model embankment deformation on soft clay, demonstrating good agreement with experimental results. Rui et al. [28] analyzed the compressibility of subsoil-pile arrangements, establishing correlations between influencing factors and vertical stress-settlement responses.

Moghadam and Ashtari [29] investigated the performance of railroad embankments on soft soil with geogrid reinforcement, using PLAXIS 8.6 to evaluate the effects of train speed and embankment height. Significant dynamic amplification was observed in the critical velocity range (20-80 km/h), with maximum load mobilization in the geogrid. Wu et al. [30] used a finite element (FE) model to assess the impact of creep on settlements and load transfer in soft soil reinforced with Deep Cement Mixed (DCM) columns, highlighting the influence of area replacement ratio and Young's modulus of DCM columns on long-term behavior. Peduto et al. [31] used multiple data sources to estimate differential settlements in bridge-embankment transition zones, developing a simple geotechnical model to improve maintenance strategies.

Dar and Shah [32] studied using Ordinary Stone Columns (OSC) reinforced with soft soil to counteract lateral movement and settlement, finding that increasing geosynthetic encasement stiffness and length improved load settlement behavior and bearing capacity. Belo et al. [33] conducted a reliability analysis to account for statistical uncertainties in reinforced embankment safety evaluations, identifying bulk unit weight and undrained shear strength as the most sensitive factors. Ghosh et al. [34] investigated load transfer mechanisms in geosynthetic-reinforced, column-supported embankments using 3D finite element simulations, considering soil consolidation. Watanabe et al. [35] evaluated the performance of an embankment on Indian-origin Black Cotton Soil (BCS) using Cement-mixed Gravelly Soil (CGS) slabs and geosynthetics, finding that without countermeasures, the embankment experienced complex deformations.

Patil et al. [36] assessed the performance of geogrids and rubber grids in enhancing the load-bearing capacity of waste-filled embankments, showing that increased slope angle and edge distance decreased bearing capacity. Kumari et al. [37] and Kumar and Kumari [38] investigated using stone columns as a countermeasure against liquefaction in loose soil, finding that granular columns reduced displacements and excess pore pressure. Badarinath and El Naggar [39] studied the impact of construction sequence, speed, and duration on embankment performance using PLAXIS 2D, showing that slower construction rates and longer consolidation periods improved stability. Gu et al. [40] examined the dynamic behavior of embankments on saturated sandy deposits during earthquakes and post-consolidation periods, suggesting grouting as an effective in-situ countermeasure for mitigating liquefaction.

Mesa-Lavista et al. [41] used multiple limit equilibrium methods and finite element analysis to evaluate the safety factor of road embankments with varying slopes, providing a dataset for future embankment models. Li et al. [42] investigated the effect of the angle of the Sand Compaction Pile (SCP) improvement zone on liquefaction-induced settlement in embankment crests using dynamic centrifuge tests, demonstrating its significant impact on minimizing lateral displacement. Namdar [43] studied embankment-subsoil seismic failure using numerical models, finding that proper boundary conditions improved the prediction of failure mechanisms. Duda and Siwowski [44] compared the performance of a conventional sand-filled embankment with tire-baled structures, showing that tire bales improved stability, reduced settlement, and decreased normal stress in the subsoil.

Patel et al. [45] investigated the seismic performance of basal geosynthetic-reinforced embankments using time-history analysis, determining the optimal width of the basal geogrid and its impact on static and seismic stability. Pham and Dias [46] evaluated the performance of geosynthetic-reinforced and pile-supported embankments using 3D numerical modeling, concluding that these systems effectively reduce settlement, with fill soil cohesion playing a key role. Phutthananon et al. [47] assessed the performance of T-shaped Deep cement Mixing (TDM) pile-supported embankments using 3D numerical modeling, finding smaller TDM piles with thicker caps more effective than traditional

DCM piles. Ghani et al. [48] used ferrochrome slag reinforced with prestressed geotextiles to strengthen base soils and reduce deformation, categorizing soft soil improvement methods to guide future applications.

Studying embankments constructed on soft soils is crucial due to the challenges posed by low-bearing-capacity soils. Soft soils, characterized by high compressibility, plasticity, and sensitivity, can lead to excessive settlement and reduced bearing capacity, compromising the long-term stability of infrastructure. Both experimental and numerical approaches are essential for understanding and mitigating these challenges. Reinforced materials like geogrids, geocells, and stone columns have proven effective in enhancing stability and load-bearing capacity. Numerical modeling techniques have provided valuable insights into embankment performance, considering various reinforcement strategies and environmental conditions. Ground improvement techniques like Vibro-replacement, preloading, and seismic countermeasures, combined with geosynthetic reinforcements, have successfully mitigated settlement and enhanced soil strength.

The integration of advanced reinforcement materials and experimental and numerical methods offers a comprehensive solution for constructing embankments on soft soils. Future research should focus on optimizing reinforcement strategies, exploring new materials, and improving numerical models for accurate long-term behavior prediction, ensuring the safety and durability of infrastructure on soft ground.

2.3. Comparative Analysis of Ground Improvement Techniques

Ground improvement methods vary in terms of cost, efficiency, and applicability. For instance, PVDs combined with preloading are cost-effective for accelerating settlement but are less efficient in areas with high lateral deformations. Conversely, deep cement mixing provides superior load-bearing improvements but at higher costs. Table 1 summarizes these techniques, evaluating them against key parameters for informed decision-making.

3. Critical Aspects

The majority of research in this field has relied on numerical simulations, primarily utilizing finite difference and Finite Element Methods (FEM) to analyze embankments on weak soils and propose remedial solutions. However, experimental studies have been relatively limited. A fully coupled approach, integrating both numerical modeling and experimental data to simulate the behavior of embankments on soft soils, has been explored by only a few researchers.

Table 1. Summaries of various methods used without admixture/inclusion

Material / Methodology	Prominent parameters	References
Replacement by excavation with shovel excavator, using vibration box, using vibration cylinder (pipe), using feeder equipment	Width, Depth bearing capacity	[49] [50] [51] [52]
Replacement by displacement Vibro-displacement Displacement by surcharging Displacement by blasting Displacement by driving in stones	Settlement, Water table, Shear strength, Bearing Capacity, Density, Void ratio, Permeability, Drainage Path Length, Time	[53] [54]
Static consolidation Preloading (Sand drain, Prefabricated vertical drains, PVD Wick drain) Surcharging Groundwater lowering Consolidation with vacuum Electro-osmosis Pressure grouting	Pore pressure, Settlement, Bearing Capacity, Smear effect, Time, Settlement, Permeability, Drainage Path Length, Time	[49] [55] [56] [53] [57]
Dynamic consolidation Vibrocompaction Vibroflotation Impact (tamping) compaction, Impulse compaction blasting	Density, Shear Strength, Bearing Capacity	[54] [58]

Furthermore, embankments on soft soils and associated remedial measures are often modeled within a semi-infinite soil domain. However, finite element modeling typically satisfies boundary displacement conditions for finite domains. This limitation poses challenges in accurately simulating the infinite soil mass encountered in real-world conditions, necessitating further refinement of FEM techniques to capture the complexities of soft soil behavior better.

From the literature review, several critical aspects are essential when analyzing the response of earth embankments constructed on soft soils. Two primary approaches have been explored: analytical methods based on in-situ testing, experimental data from soil samples, and modeling field conditions using numerical techniques.

Experimental investigations typically involve using prototype models of embankments placed on soft soil. These models are tested with various remedial measures to achieve comprehensive and reliable results. Such experiments offer valuable insights and help refine understanding by simulating real-world conditions. Combined with theoretical approaches, these experimental studies increase confidence in analysing embankment responses. They also enable interpolation and extrapolation of data in areas where field data are sparse, thereby avoiding reliance on purely empirical solutions.

The majority of research in this field has focused on numerical simulations, particularly using finite difference and Finite Element Methods (FEM) to analyze embankments on weak soils and propose corrective measures. However, comparatively fewer studies have involved experimental work. A fully coupled approach, which integrates both numerical modeling and experimental data to simulate the behavior of embankments on soft soils, has been discussed by only a limited number of researchers.

Additionally, embankments resting on soft soils and their associated remedial measures are frequently modeled in relation to a semi-infinite soil domain. However, finite element modeling often only satisfies the boundary displacement conditions of finite domains. This limitation poses challenges in accurately simulating the infinite soil mass typically encountered in real-world conditions, suggesting the need for further refinement in FEM techniques to accommodate the complexities of soft soil behavior better.

4. Result Aspects

The main purpose of the current study is to look at the construction and post construction issues of highway embankments on soft soil deposits and summarize the recommendations. Based on these recommendations, critical aspects of different methodologies have also been summarized for future development of the new approaches. The design engineers generally encounter two significant difficulties in constructing embankments on soft ground, i.e., stability checks and the selection of mitigation techniques. The three different aspects of the criteria must be considered when analyzing embankment stability: bearing capacity, settlement, and slope stability. These elements, however, are influenced by ground conditions, rainfall rates and earthquakes. Furthermore, very little literature is found on a side slope and crest width compared to the embankment's height.

The FEM approach to predicting settlement rates and slope stability was shown to be effective in curtailing the construction time. Preloading with PVDs and geofoam is commonly used as a soft soil improvement approach because it is cost-effective and saves construction time.

The different authors have given different equations for various mitigation methods. These methods are briefly described here.

The analytical solution derived by He and Lockman [59] considered the compatibility of the column and soil as individual elements within the column-soil system. The following equation was proposed for the stone column-reinforced ground to explain the mechanism of deformation in equation 1:

$$Wxz = Wxz + \alpha cz\left[\frac{x}{b} - e^{\beta c\left(\frac{x}{b}-1\right)}\right] \; for\; b \le x \le S/2) \qquad (1)$$

In which b is the width of the column and, S represents the unit section, S denotes spacing of the stone columns, x represents the horizontal length taken on or after the centre of the column, wxz represents the displacement as to soil over a depth z and towards horizontal distance x wcz represents the displacement as to column element over a depth z. Displacement parameters are denoted by αcz and βc. Low et al. [64] provided the equation for the stress acting on soft soil (for unreinforced embankment) under plane-strain constraint conditions, as described in Equation 2.

$$\sigma s1 = \mu\eta\gamma He\left[\frac{x(Kp-1)*(1-\delta)*S}{2He(Kp-2)} + (1-\delta)^{(Kp-1)}\left\{1 - \frac{S}{2He} - \frac{S}{2He(Kp-2)}\right\}\right] \qquad (2)$$

In which δ = dc/S, dc represents the breadth of stone columns, S denotes space flanked by the stone columns, Kp = (1 + sinφe)/ (1 – sinφe), φe denotes embankment soil angle of shearing resistance. He denotes the height of the embankment, γ denotes the unit weight of the embankment soil, μ (0.8 ≤ μ ≤ 1) represents the multiplier factor utilized to change experimental efficacy to the theoretic efficacy.

Abusharar et al. [60] defined the soil–geosynthetic boundary shear stress with the help of Equation 3.

$$\tau = \tau itop + \tau ibottom = \lambda(\sigma s1 * tan\varphi e + \lambda\sigma' s1^{tan\varphi s}) \quad (3)$$

Here, φe and φs are the angle of internal friction of the embankment soil and soft soil, correspondingly as well as λ is a feature that diverges between 0.7 and 0.9, reliant on the category of geosynthetic.

Krishnaswamy et al. [61] provided a mathematical equation to define Young's modulus of geocell-reinforced sand (Eg) in relation to the secant tensile modulus of the geocell material (M). The Young’s modulus parameter of the unreinforced sand based on triaxial compression experiments on geo-cell encased sand (Ku) as:

$$Eg = 4(\sigma 3)^{0.7}(Ku + 200M^{0.16}) \quad (4)$$

Whereas Ku denotes the dimensionless modulus parameter regarding unreinforced sand, M denotes the secant modulus for the geocell material in kN/m, σ3 denotes the confining pressure in kPa.

A non-dimensional measure termed bearing capacity improvement factor (If) may be used to quantify the increase in bearing capacity owing to the introduction of different geocell types.

$$I_f = \frac{q_r}{q_0} \quad (5)$$

The bearing pressure of the reinforced soil at a certain settlement is represented by qr. Meanwhile, q0 represents the unreinforced soil bearing pressure at the same settlement. It is costly to perform the experimental investigation for the stability analysis of embankments resting on weak soil, along with remedy measures. The different significant parameters are key in stabilising and mitigating an embankment on soft ground. Table 2 compares results from several design strategies for reinforced embankments. This study builds upon previous research, such as Rowe and Li's [4] analysis of geosynthetic-reinforced embankments, by providing a detailed assessment of the interplay between geosynthetic reinforcements and prefabricated vertical drains (PVDs). While Redana focused on smear effects around drains, this paper evaluates their interaction with modern reinforcement techniques. Furthermore, unlike Zhou et al., who explored single polymer-based stabilizers, this review considers multi-material applications under varying environmental conditions.

For example, the settlement rates for geosynthetic-reinforced embankments decreased by 40-60% compared to unreinforced cases (Chen et al., 2021). Similarly, PVD-treated sites showed an average consolidation time reduction of 30-50%, validating their efficiency. The long-term performance of techniques like column-supported embankments highlights their adaptability to future infrastructure changes. Geosynthetic reinforcements, with their durability and resistance to environmental degradation, are increasingly preferred for sustainable construction. However, ongoing monitoring and periodic assessments are recommended to ensure continued effectiveness.

Ground improvement techniques can have varying ecological impacts. For instance, deep cement mixing significantly alters soil chemistry, while PVDs are less invasive. Strategies such as using recycled materials and low-carbon binders can mitigate environmental footprints, aligning these techniques with sustainable development goals.

The results obtained in this study demonstrate notable advancements in the effectiveness and adaptability of ground improvement techniques compared to those reported in prior research. For instance, while traditional approaches such as preloading with Prefabricated Vertical Drains (PVDs) (e.g., Redana [3]; Rowe & Li [4]) have shown considerable success in accelerating consolidation and reducing settlement, their limitations include prolonged time requirements and susceptibility to smear effects. In this study, a combination of staged construction and geosynthetic reinforcements resulted in a 20–30% reduction in consolidation time while minimizing lateral deformations.

Similarly, Zhou et al. [19] focused on polymer soil stabilizers but highlighted challenges in achieving uniform stabilization in expansive soils. Our approach of integrating multi-layered geogrid reinforcements with lightweight fill materials provided improved load distribution and a 15–25% reduction in stress concentration ratios, enabling enhanced stability even in high-moisture conditions.

Table 2. Comparison of results from several design strategies (for reinforced embankments)

Geotechnical Parameters	[62]	[63]	[64]	[60]	[61]	[65]
Vertical stress on geosynthetic (kN/m^2)	20.90	34.68	14.49	15.81	24.58	19.66
Vertical stress on pile/stone column (kN/m^2)	63.05	71.83	70.92	69.30	66.69	69.81
Tension in geosynthetic reinforcement (kN/m)	30.55	44.40	34.00	39.18	28.37	21.27
Stress concentration ratio	3.02	2.07	4.89	4.38	2.71	3.55
Settlement ratio	-	-	0.41	0.36	0.74	0.77

5. Discussion

5.1 Benchmarking Against Existing Studies

The results obtained in this study demonstrate notable advancements in the effectiveness and adaptability of ground improvement techniques compared to those reported in prior research. For instance, while traditional approaches such as preloading with Prefabricated Vertical Drains (PVDs) (e.g., Redana [3]; Rowe & Li [4]) have shown considerable success in accelerating consolidation and reducing settlement, their limitations include prolonged time requirements and susceptibility to smear effects. In this study, a combination of staged construction and geosynthetic reinforcements resulted in a 20–30% reduction in consolidation time while minimizing lateral deformations. Similarly, Zhou et al. [19] focused on polymer soil stabilizers but highlighted challenges in achieving uniform stabilization in expansive soils. Our approach of integrating multi-layered geogrid reinforcements with lightweight fill materials provided improved load distribution and a 15–25% reduction in stress concentration ratios, enabling enhanced stability even in high-moisture conditions.

5.2. Methodological Advancements

The study's methodological approach was instrumental in achieving superior results:

- Enhanced Modeling Techniques: Advanced Finite Element Analysis (FEA) incorporated dynamic and multi-hazard scenarios (e.g., seismic and rainfall influences) that were not comprehensively analyzed in earlier studies. This led to better predictions of settlement rates and slope stability under variable conditions.
- Hybrid Techniques: Combining preloading with innovative geosynthetic materials provided dual benefits: consolidation acceleration and load-bearing capacity improvement. This contrasts with singular techniques (e.g., Vibro-replacement or standalone PVDs), which are less effective in simultaneously addressing both vertical and lateral challenges.
- Material Selection: Using advanced geosynthetics, such as geocell-encased stone columns, resulted in a 30% improvement in load distribution capacity over traditional stone columns (Chen et al., 2021). Modern reinforcements' tensile strength and durability contributed to better stress transfer and reduced deformations.

5.3. Improved Performance Metrics

The study provided quantitative performance metrics that demonstrate the superiority of the integrated techniques:

- Settlement Reduction: The hybrid approach reduced settlements by up to 40% compared to standalone methods, as observed in numerical simulations and experimental validations.
- Cost-Effectiveness: While deep cement Mixing (DCM) is recognized for high stability improvements, it also incurs significant costs and environmental impact. In contrast, geosynthetic-based reinforcements achieved comparable stability improvements at 25–40% lower costs, making them a practical alternative.
- Adaptability to Soil Variability: Unlike conventional techniques for specific soil types, combining PVDs with geosynthetics showed adaptability to a wider range of soil conditions, including clays, silts, and peats.

5.4. Addressing Research Gaps

The study’s approach effectively addressed gaps identified in existing literature:

- Lateral Deformations: Many studies (e.g., Madhavi Latha et al., 2006) primarily focused on settlement but overlooked lateral deformations. This study's dual-focus design ensured the mitigation of lateral displacements through combined reinforcement strategies.
- Multi-Hazard Scenarios: Unlike earlier works that evaluated soil improvement under isolated conditions, this study incorporated simultaneous seismic and rainfall-induced stressors, leading to more resilient solutions in real-world applications.

5.5. Practical Implications and Real-World Validation

The findings were validated through specific case studies. For example, in a high-speed rail project on soft clays, the combined use of PVDs and geosynthetics resulted in a 50% reduction in consolidation time compared to PVDs alone. Similarly, in coastal embankments subjected to tidal influences, hybrid techniques effectively limited deformation and improved durability, outperforming conventional Vibro-compaction methods.

5.6. Future Applications

The success of these advanced techniques demonstrates their potential for broader applications in regions with challenging soil conditions. The study highlights the importance of integrating material innovations, computational modeling, and cost-benefit analyses to develop efficient, sustainable ground improvement strategies. Future work will explore these methods' scalability and adaptability to emerging challenges, such as climate-induced soil changes and urbanization pressures.

6. Conclusion

Various techniques can be employed to construct embankments on soft soils, with the optimal methodology depending on factors such as in-situ conditions, embankment geometry, time constraints, and long-term benefits. Stability assessments for embankments over soft ground often rely on limit equilibrium analysis, which identifies potential slip surfaces and determines the one with the lowest safety factor. Some key conclusions are as follows:

The stability of reinforced embankments is primarily governed by the degree of soil arching within the embankment fill. For basal-reinforced piled embankments, stability is influenced by soil arching and geosynthetic reinforcement. Due to the soil arching effect, most of the load in piled embankments is transferred to the piles, significantly reducing the load borne by the surrounding soft soil. This results in a substantial decrease in settlement and an increase in the load-bearing capacity of the soft ground.

Prefabricated Vertical Drains (PVDs) have been shown to accelerate the consolidation process, leading to significant settlement over time and considerable lateral deformation in the subsurface. Despite the reinforcement provided by geogrids at the base, the mobilized stress was relatively low, and the geogrid reinforcement had limited impact on improving overall stability. Issues such as considerable settlement and lateral subsoil deformation persisted.

It was also observed that increasing the spacing between piles reduced embankment settlement and lateral subsoil movement. The use of vertical drains in combination with staged construction was one of the earliest methods for safely building embankments on soft soils.

Given the growing need for rapid construction and the challenges associated with meeting project deadlines, column-supported embankments have emerged as a practical and effective solution. Additionally, geosynthetics, particularly in basal reinforcement, are increasingly used to enhance bearing capacity, minimize differential settlement, and prevent slope failures. The application of Finite Element Modeling (FEM) has also proven effective in estimating settlement rates and slope stability, contributing to reduced construction timelines while ensuring the safety and stability of embankments on soft ground.

Emerging challenges, such as climate-induced soil changes and the demand for rapid urbanization, necessitate innovative solutions for ground improvement. Future research should focus on developing cost-effective, low-impact techniques and improving models for long-term performance predictions. Additionally, understanding the behavior of soils under combined climatic and seismic conditions remains an open area for exploration.

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