

Ground Improvement Techniques for Soft Soils: A Comprehensive Review

Lutufullah Muzammal¹, Hidayat Ullah², Muhammad Nouman Sattar³, Muhammad Ali Hasnain⁴, Muhammad Qasim Toor⁵, Rabnawaz⁶, Ar. Samiullah Memon⁷

¹Faculty of Business and Management Sciences, The Superior University, Lahore, Pakistan
muzammil108@hotmail.com

²Hdesigns, Quetta, Pakistan, hidayatkakar7@gmail.com

³Department of Civil Engineering, National University of Technology (NUTECH), Islamabad, 44000, Pakistan, drnoumansattar@nutech.edu.pk

⁴PG Researcher, MS Geotechnical Engineering, National Institute of Transportation (NIT), National University of Sciences and Technology (NUST), Islamabad, Pakistan, engralihasnain12@gmail.com

⁵MS Construction Engineering Management, Texas Tech University, Texas, USA, qasimtoornl@gmail.com

⁶Department of Civil Engineering, University of Engineering and Technology, Taxila, Pakistan, rabnewazbhatti11@gmail.com

⁷Mehran University of Engineering and Technology, Jamshoro, Pakistan, ar_samiullah45@yahoo.com

Abstract

Soft soils such as clay, silt, and organic deposits present significant challenges for civil engineering projects due to their low bearing capacity, high compressibility, and excessive settlement potential. These unfavorable geotechnical properties often threaten the stability and serviceability of infrastructure including highways, embankments, bridges, and building foundations. Consequently, ground improvement techniques have become essential to enhance soil strength, accelerate consolidation, and reduce long-term settlement. This review paper presents a comprehensive analysis of major ground improvement techniques used for soft soil stabilization, focusing on mechanical, chemical, and inclusion-based methods. Mechanical techniques such as preloading, vacuum preloading, and prefabricated vertical drains (PVDs) are widely applied to accelerate consolidation and improve soil density by expelling excess pore water pressure. Chemical stabilization methods, including cement stabilization, lime treatment, deep soil mixing, geopolymers, and bio-based techniques like microbial-induced calcium carbonate precipitation (MICP), modify soil structure through chemical reactions that increase strength and stiffness. Inclusion-based approaches such as stone columns, geosynthetic reinforcement, and reinforced columns improve load transfer mechanisms and reduce settlement by creating composite ground systems. The paper also evaluates performance metrics including settlement reduction, consolidation acceleration, and cost effectiveness based on reported case studies and experimental research. In addition, emerging sustainable technologies such as biodegradable vertical drains, recycled materials, natural fiber reinforcement, and electrokinetic stabilization are examined for their environmental benefits and engineering potential. The findings indicate that hybrid ground improvement systems combining multiple techniques often provide the most effective solutions under complex site conditions.

Keywords: Soft soil stabilization; Ground improvement techniques; Prefabricated vertical drains (PVD); Deep soil mixing; Stone columns; Soil stabilization; Geosynthetic reinforcement; Microbially induced calcium carbonate precipitation (MICP); Settlement reduction; Sustainable geotechnical engineering.

INTRODUCTION

The existence of soft soils with low bearing capacity, high compressibility, and high-water content poses a big challenge to engineers in the process of undertaking civil construction projects (Husaini et al., 2025). Such soils as clays, silts and organic deposits are common in most parts of the world and they need a special kind of treatment before they can be able to support structures adequately. The engineering problems of soft soils are not new, the most important concerns in the development of infrastructure are settlements, the collapse of the bearing capacity, or stability. Ground improvement is an essential remedy to the issues, and the problematic soils are converted into materials that can sustain permanent buildings in a safe and cost-effective manner (M, 2025).

The need to have ground improvement methods has been felt more and more as urbanization spreads to the geologically unfavorable areas. Highways, bridges, embankments and building foundation are some of the major infrastructure projects that often face soft soil deposits which need to be remedied before the construction process can begin. Examples of problematic soils used in construction that lead to problems in the project include soft clays and organic deposits, which, when used in construction, may lead to uncontrolled settlement, differential settlement, slope instabilities, and in worst-case scenarios, the structure may fail (M, 2025). The conventional methods of merely excavating the soft soil and substituting it with quality fill material are sometimes economically inadvisable particularly when the size of the area is huge and/or the depth of the bad material is great. This economic limitation has prompted massive research and development of new ground improvement methods that stabilize ground in situ and lowers the cost of the projects and environmental effects.

Ground improvement represents a wide variety of approaches that can be organized into three key methods, namely, the mechanical, the chemical, and the inclusion-based methods (M, 2025). The methods can be either mechanical, like the use of vibration, preloading or consolidation acceleration, which involves rearrangement of the particles of soil and the expulsion of water in order to enhance the density and strength of the soil. Chemical techniques, such as stabilization of cement and lime, change the basic characteristics of soil, by chemical reactions that cement particles, or by decreasing water content. The methods of inclusion add new materials like stone columns, geosynthetic, and fiber reinforcement to add to the bearing capacity and settlement. Both methods have their unique pros and cons, and the choice of the suitable methods is limited to the specific features of the sites, needs of the project, and finances (Husaini et al., 2025).

Environmental and sustainability features of ground improvement are becoming major concerns when considering the modern geotechnical engineering practice. According to recent studies, ground improvement techniques based on recycled and waste materials will have a tremendous benefit in relation to environmental sustainability, such as a reduction in carbon footprint, preservation of the natural resources and enhanced management of waste (Elyiğit, 2025). Recent research has increasingly focused on the utilization of waste-derived materials for sustainable ground improvement and construction applications. Studies have shown that materials such as waste glass powder and polymer-based waste can significantly enhance geotechnical and mechanical properties while reducing environmental impact [Khan et al., 2018; Khan et al., 2021].

With a vast number of materials recycled and a large number of techniques being locally sourced or using industrial waste products, unlike the traditional techniques of soil replacement, which result in the production of large amounts of waste, many of the new techniques of ground improvement ensure that waste is minimized. Also, the ground improvement methods that promote natural processes of consolidation use the existing soil properties, instead of applying artificial environments, which is a more compatible method to engineering in complicated geological formations (Husaini et al., 2025).

Site investigation, characterization and design are critical in determining the success of ground improvement projects. Detailed knowledge of the soil properties such as grain size distribution, mineralogical composition, water content, and index properties are necessary towards the choice of the proper treatment measures. Moreover, soft soil deposits depth and extents, the presence of contamination, and groundwater characteristics determine the choice of techniques and the design parameters (Das, Islam and Datta, 2025). The use of sophisticated testing approach, numerical modeling and risk analysis is increasingly employed in the design process allowing more efficient and economical solutions. The blending of established geotechnical experience and modern analysis tools has opened up the pool of viable options to address difficult conditions of soft soil (Husaini et al., 2025).

The last 20 years have seen a rapid increase in technological innovations in the field of ground improvement because of the possibilities of computer-aided design, better construction devices, and increasing the amount of performance data available based on the completed projects. Adaptive management of ground improvement processes is now possible through real-time monitoring systems whereby changes can be done depending on the performance that is being observed. Finite element and finite difference numerical modeling allow a deeper insight into the behavior and process of soil in the course of improvement and optimization of design parameters. Additionally, the consideration of sustainability in the design of ground

improvement has led to the creation of ecologically friendly methods, which reduce the use of resources and environmental effects (Sim et al., 2024).

The literature review is a synthesis of the existing information on ground improvement methods that may be used in case of soft soils, but it focuses on the analysis of mechanical, chemical, and inclusion-based techniques. Each technique has a number of basic principles, which are discussed in the review, practical applications to different types of soils, project conditions, methodologies to evaluate the effectiveness, economic factors, and innovations, which are discussed. General ground improvement procedures have shown that ground improvement methods have their strengths and weaknesses but a cooperation of the methods may prove the best outcome depending on the conditions that are present in the site (Husaini et al., 2025). This document is a resource to engineers, researchers and decision makers in engineering and executing ground improvement projects in soft soil because it offers an in-depth review of the state of practice and knowledge on the subject (Gali et al., 2023; Shah et al., 2023; Khan et al., 2025; Nawaz et al., 2025).

Mechanical Ground Improvement Techniques

Preloading is one of the most basic and the most common ground improvement method of using soft soils. Another useful method of ground improvement is preloading with vertical drains that is applied to speed up the process of consolidation (Cui et al., 2024). The method is the use of surcharge pressure to the soft soil layers and water is forced out and permanent settlement is achieved before construction of permanent buildings. The Accelerated consolidation under pre load condition leads to a reduction in the void ratio of the soil and an increase in the effective stress with resultant increase in the bearing capacity and consequently a tremendous reduction in settlement after the construction. Learning how to work with soft soils, the preload is supported by a filtering embankment with vertical drains that enhance the bearing capacity of the foundation and strengthen the vertical drains in a short-term condition, which is why it is possible to use the structures without any severe additional deformations (Tregub et al., 2025).

The drainage properties of soil deposits are critical factors to the effectiveness of preloading. Consolidation is fast in sandy soils with high permeability and settlement reduction is achieved quite fast with preloading in these soils. In contrast, when the ground is of low permeable clay, the process of soil consolidation is slow and long preloading time may be necessary to attain the desired reduction in settlement. Theoretical solutions can be used to compute the degree of consolidation at any time and this allows the engineers to determine the time taken during preloading. It has been shown that prefabricated Vertical Drain (PVD) and Vacuum Preloading is a technology that can decrease the land subsidence and hasten the consolidation processes and preloading method using PVD is one of the most effective tools which have the ability to reduce the settlement (60 percent) and shorten the time of consolidation (4.2 times faster) (Rahayu, Norfajriati and Octarinie, 2025). A number of variations of preloading have been formulated so as to hasten the consolidation process and to enhance its economic feasibility. The simplest method is fill preloading, when soft soil is covered with temporary or permanent fill material to exert surcharge pressure, which is a method that needed large amounts of material and controlled use of temporary fills. The use of a vacuum preloading, where negative pressure is used at the surface of the soil to increase the load of surcharge, has been particularly efficient in producing a high rate of consolidation, and can save the length of treatment by a significant margin. Moreover, when preloading is combined with other methods, including prefabricated vertical drains, consolidation rates are increased tremendously because the long paths of drains are shortened (Kartawiria et al., 2025).

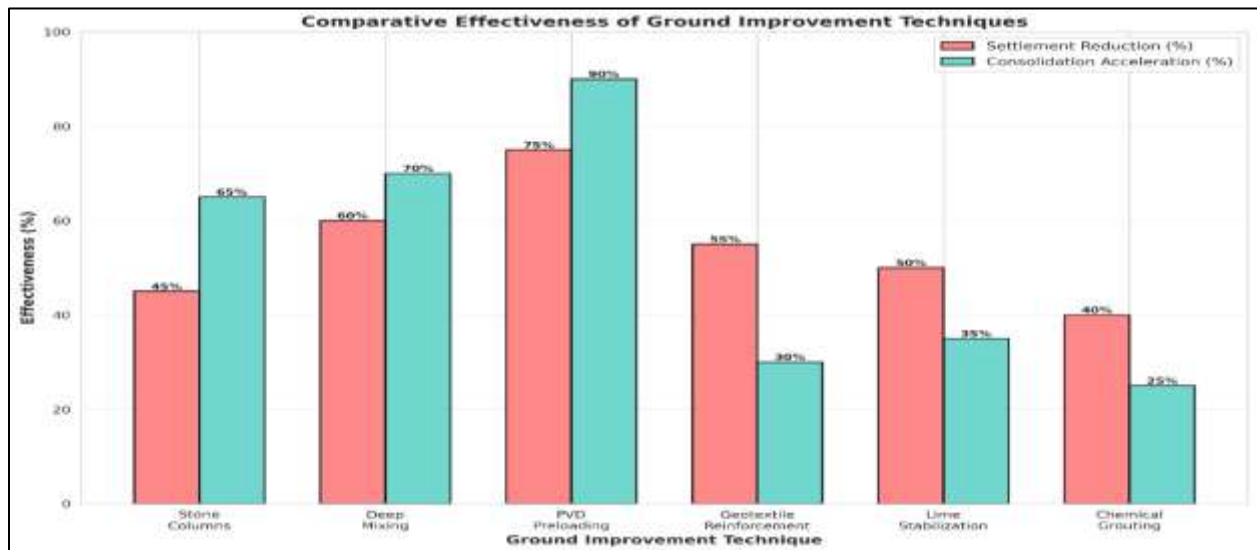


Figure 1 *Comparative Effectiveness of Ground Improvement Techniques*

Prefabricated vertical drains (PVDs), wick drains, or band drains are structures that have transformed the management of the soft soil deposit by significantly enhancing the rate of consolidation (Raines et al., 2024). These artificial drainage components are composed of an open plastic core that is enclosed in a filter material of geotextile type and this element serves to form the vertical drainage channel which minimizes the horizontal distance that water is required to travel during the consolidation process. PVDs lower the time taken to consolidate the soil of potentially tens of meters to a normal less than a meter or two, which essentially increases the feasibility of projects in soft soil locations. Studies reveal that full-depth PVDs installation has always yielded better settlement result with peak values of up to 3.13 meters, and can settle within 25 weeks, which is the best component that can be used to confirm the enhanced effectiveness of full-depth PVDs in hastening the process of consolidation (Raines et al., 2024).

PVDs design and installation should be carried out with the proper regard to the characteristics of soils, the distances between drains, installation procedures, and peculiarities of the work to guarantee optimal functionality (Thirmanpalli, Kommu and Kadali, 2024). The effective drainage path length and therefore the rate of consolidation is regulated by the distance between the drains, which is usually between 0.5 and 2.5 meters depending on the permeability of the soil and the project requirements. Once the installation is done, specialized machinery is normally used such as mandrels and displacement systems that bore little diameter holes in soft soil through which drains are placed, which cause minimum disturbance to soil. Vacuum consolidation also minimizes the time of consolidation and enhances the evacuation of the surplus pore water pressure (Raines et al., 2024). Surcharge preloading is synergistic with PVDs, thus hastening the rate of consolidation significantly faster than either of the two approaches would achieve by itself (Thirmanpalli, Kommu and Kadali, 2024).

The process of monitoring and performance verification of PVD systems has become more advanced as better means of instrumentation and data collection means are developed. Piezometers, inclinometers and settlement plates located over both the treated areas give real-time information on the progress of consolidation and thus allow adaptive management of preload timings and surcharge magnitudes. The pore pressure measurements are also useful because reduction of excessive pore pressure is an indication of consolidation regardless of the size of settlement, which may be affected by other factors. The use of automated data collection and remote transmission of the results of the projects is a growing practice in modern projects, as it allows the remote monitoring and prompt response to performance changes in expansive treatment areas (Ramilo, Haxell and Cole, 2025).

Granular piles or Stone columns otherwise known as stone columns are a common inclusion method of enhancing bearing capacity and limiting settlement of soft deposits of soils (M, 2025). The method is by placing separated by fine spacing columns of compacted granular material (usually gravel or crushed stone)

through soft layers of soil to form a composite system of soil-stone columns that have even greater load-bearing qualities. Stone columns are used to redistribute loads, speed up the process of consolidation, and increase drainage which is a specific use of them in the case of soft clay and loose sand areas (M, 2025). Installation normally uses vibration-assisted displacement techniques whereby a vibratory probe is used to form a cavity through the soil layers and at the same time introduce granular material, which is compacted when the probe is removed.

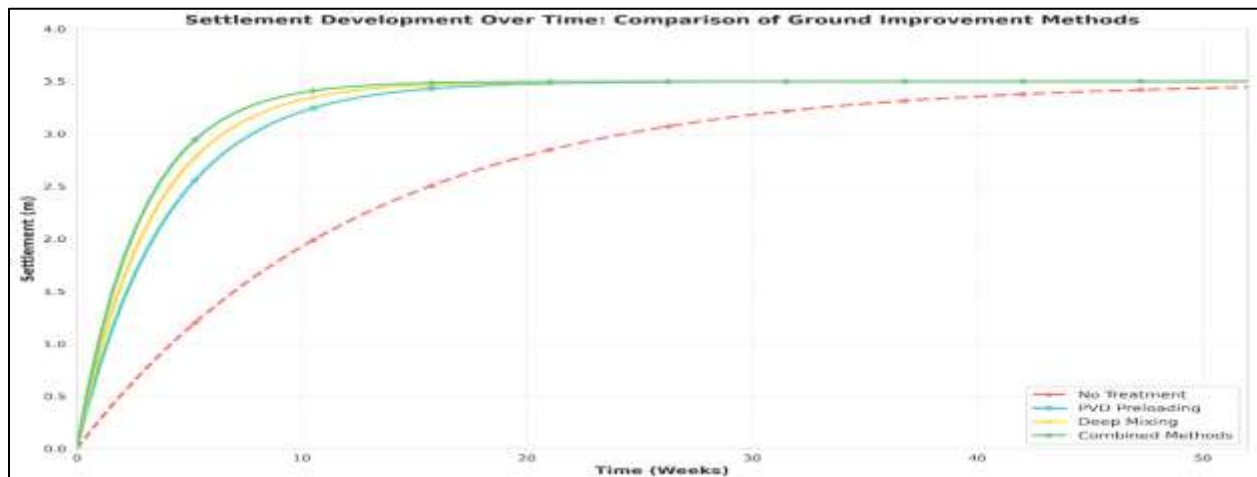


Figure 2 Settlement Development Over Time: Comparison of Ground Improvement Methods

The stone column improvement mechanism has two main effects, direct load transfer by use of stiffer stone material and stress concentration effects that in turn stiffen the surrounding soil matrix. The stone column is an enhancement method of geotechnical engineering to improve the load-bearing nature as well as draining characteristics of weak or soft soils (Shahid et al., 2025). These columns work through the formation of vertical reinforcement features and redistribution of stresses and overall soil behaviors. A detailed analysis of ground improvement method of strengthening load-bearing capacity proves the usefulness of stone columns in stabilizing weak soils and offers cost-efficient and natural environmental solutions (Chaudhary, 2024). Field measurements and case histories have been widely used in documenting actual performance of stone columns. Studies show that in cases where stone columns are used, the stone columns will greatly lower settlement and speed up the dissipation of pore pressure (Yuvraj and Kumari, 2025, Robinson, Thilakarathne and Thilakasiri, 2024).

CHEMICAL STABILIZATION METHODS

Deep mixing is a contemporary in-situ soil enhancement procedure that can be used to combine stabilizing agents in the entire deposits of soft soils without digging or removal of materials (Husaini et al., 2025). DSM has become a promising in-situ stabilisation method, which has the potential of improving weak soils to become materials that can be used to support structures (Rajanayake and Sampath, 2025). The method involves the use of special drilling tools comprising of rotating mixing paddles that inject binder slurry (usually cement or lime) into the soil in place and mixes it thoroughly at the same time. Deep mixing can also be applied to difficult stabilization issues in the subsurface because any depth of between 10 and more than 60 meters can be achieved depending on the equipment setup and the composition of the soil (Nguyen, 2023). Mixing effectiveness and efficiency of deep mixing require that there is sufficient mixing between injected binder and in-situ soil. It was found that laboratory tests on deep soil mixing columns show outstanding enhancements to soil properties and the average of unconfined compressive strength (UCS) of peat columns treated is 706 kPa relative to 120 kPa in untreated peat columns, which indicates a significant increase in load-bearing capacity (Rajanayake and Sampath, 2025). Moreover, deep mixed samples revealed nearly 55 to 60 percent settlement limitation of peat in typical loading conditions than untreated peat, and it confirms the efficacy of the treatment (Rajanayake and Sampath, 2025). Different scholars have suggested the combination of indices in order to measure consistency of stabilization and relation to overall system

performance. The further and closer the Deep Mixing Column applied the less the fall and the less time is taken to consolidate (Hamdhan and Raasyid, 2025).



Figure 3 *Classification of Ground Improvement Techniques*

Deep mixing has widely been utilized in Japan, Scandinavia and other locations to a growing degree to ensure the stabilization of soft clay beds under buildings, embankments and marine structures. The viability of shallow foundations using ground improvement methods like PVDs and stone columns is studied numerically and proves that deep mixing columns improve the strength of the soil and fasten the process of consolidation (Thirmanpalli, Kommu and Kadali, 2024). Case study performance data has shown effectiveness in attaining significant settlement reduction and bear capacity enhancement, with case studies showing construction over deep-mixed deposit with the least amount of post-construction settlement (Thang, 2023). Nevertheless, the equipment needed and skill possessed to ensure the best parameter choice somewhat restrict the availability of deep mixing over the less complex methods. Among the most popular and widely used ground improvement methods, cement stabilization is a slow mortar made by mixing the Portland cement or other cementitious materials with loose soils to form cemented and high-strength materials (Husaini et al., 2025). The chemical reaction between cement and soil particles forms cementing compounds which cement soil particles, which significantly enhance bearing capacity as well as decrease compressibility. Fine cohesive soils, especially those containing clay minerals, are especially responsive to cement stabilization by the reaction of pozzolans that form powerful links between particles (Husaini et al., 2025). The latest studies surrounding the stabilization of soft clay soils indicate that recycled and the small proportions of cement in the stabilization of soils create the environmentally sustainable environment and enhanced performance of the engineering (Fadhil and Ahmed, 2025). The highest improvement in unconfined compressive strength (UCS) was obtained at the 2.5 percent content of plastic waste, and large UCS improvement was obtained upon the inclusion of cement and recycled plastic waste mixture than when the cement was applied only (Fadhil and Ahmed, 2025). The method offers both environmental advantages and better geotechnics thus it is a more appealing choice to consider in terms of sustainability.

Geopolymers are produced by alkaline activation of aluminosilicate raw materials such as fly ash and metakaolin; geopolymers have the potential to be sustainable by using raw materials in the form of industrial waste products. It is also shown that the assessment of geotechnical properties of clayey soils treated with geopolymers proves that the compression index should decrease, whereas unconfined compressive strength should increase with the increase in the geopolymer content, and the results indicate that the values should be raised by 125% (Yassin, Abdulrasool and Al-Adili, 2025). Field application of geopolymer stabilization is still in its practical stages of implementation as compared with traditional binders, and most of the current uses of the technology have been in research and pilot projects. Nevertheless, the eco-friendly advantages of using the large amounts of industrial by-products have given rise to further research and development.

Natural fiber reinforcement is a relatively new method of ground improvement, which utilizes sustainable materials to improve the properties of the soil. Poor soils may be having low bearing capacity as in the case of soft clay, which requires ground improvement strategies to provide structural stability, and one of the potential approaches to soil reinforcement is the addition of natural fibers, specifically coconut coir (Putra and Widiанти, 2026). Coconut coir fibers have the potential of reinforcement of soil using natural fiber-based stabilization systems (Putra and Widiанти, 2026). The impact of sodium hydroxide treatment on coconut coir fibers and its impact on splitting tensile strength of soilfiber mixtures have been studied to explore the possibility of using chemical treatment to increase bonding with soil particles (Putra and Widiанти, 2026).

In a detailed experimental analysis, it is established that coir fiber is a major strength enhancer to unconfined compressive strength when incorporated in the soil (Dasaka and Sumesh, 2011). This directly depends on the amount of use and optimum fiber-reinforced strength with 1.5% coir content is over two times greater than the non-reinforced soil (Dasaka and Sumesh, 2011). More than that, nylon fiber content shows that the more content in the product, the lower the liquid limit and higher the plastic limit as well as compression index, which reduces to 43 percent (Salim, Al-Soudany and Jajjawi, 2018). These natural fiber applications are environmentally friendly in that they enhance soil engineering characteristics.

Biocementation is another of the new-fangled bio-based ground enhancements, which can enhance the engineering conduct of soils by the congealing of calcium carbonate minerals (Gomez et al., 2025). The geotechnical engineering property of soils solidified through microbially induced CaCO₃ precipitation (MICP) proves that using metabolic activity of microbes to perform biochemical reactions is enabled through microbially induced calcium carbonate precipitation (Liu, Li and Li, 2021). By using regulated development of inorganic minerals, the soil particles become cemented and soil pores are sealed to solidify the soil and decrease its permeability, and such applications are expected in geotechnical engineering, among others, to build antiseepage and the ability to resist the foundation erosion (Liu, Li and Li, 2021).

Inclusion-Based and Reinforcement Methods

Geosynthetic Reinforcement and Ground Stabilization

Geosynthetic materials, such as geotextiles, geogrids, or geomembranes, have also gained increasing significance in ground improvement of soft soil by the ability to offer tensile reinforcement, drainage facilitating and separation capabilities. Geosynthetics of the right type, when installed in soft soil under embankments or buildings, spread the loads applied to them more evenly, eliminating stress concentrations, and allowing the construction of embankments to steeper slopes or higher heights than would otherwise be possible without reinforcement (Husaini et al., 2025). A study of the reinforcement of woven geotextile proves that bearing capacity significantly increased with the reinforcement of a square foundation with woven geotextile system, and the final bearing capacity increased approximately 1.91 times when the foundation was reinforced with three layers of the woven geotextile (Thageel and Shaia, 2024). Separation using geosynthetics (geotextile) and reinforcement using geogrid (geosynthetic) shows the enormous fulfilment of geosynthetic reinforcement on the construction of a building on soft clay soils (Haritha and Krishnamurthy, 2023). Field tests like modulus of subgrade reaction test and plate load test were performed on better ground to determine the quality of improvement and results indicated that bearing capacity was significantly increased (Haritha and Krishnamurthy, 2023). Geosynthetic-reinforced soft soil systems have to be designed with close attention to the necessary reinforcement strength, bonding with other constructions and the mechanisms of

interactions between the geosynthetic material and the surrounding soil. The reduction of the settlement under such systems is usually between 20-40 percent depending on the reinforcement properties and the layer structure. The hybrid reinforcing method will be narrowed down to using bamboo mattresses, high-strength woven geotextile, PVD and staged embankment construction to address shear strength and settlement issues in difficult soft soil conditions (Kartawiria et al., 2025). The mattress is used as a platform and is configured to sink to a maximum of the soft soil to even out initial embankment load evenly and enhance bearing capacity, and the powerful woven geotextile gives tension capacity (Kartawiria et al., 2025). It is a holistic strategy that proves the success of the integration of several reinforcement techniques to produce high ground improvement results.

Reinforced Stone Columns and Encasement Methods

Reinforced stone columns are a development of the traditional stone columns by the incorporation of geosynthetic encasing which enhances strength and limits lateral spreading. A study of stone columns in unengineered closed landfill soil shows that the final bearing capacity was enhanced by 75-112.50 per cent and 87.50-176 per cent respectively when an unreinforced stone column is installed in the soil (Singh and Garg, 2021). Moreover, the ultimate bearing capacities of geogrid-enclosed stone column on maximum reinforcement of 156.25-212.50 and 200-298, prove the significant effect of reinforcing the column (Singh and Garg, 2021). The layer of geogrid entraps the aggregate, which leads to the increase of shear resistance and bearing capacity. Stone columns have been used successfully in applications of embankment with a steady increase in performance. An example of a case study consists of investigating stone columns strengthening of soft soils on embankments which proves to have the ability of enhancing weak soil characteristics, and the method can be used as a cost-effective approach to support compressible cohesive soils (Nehab et al., 2014). The analysis of numerical reinforced embankment on soft foundations through the use of stone columns confirms that stone columns have a major role to play in settling and dissipating the pore pressure (Yuvraj and Kumari, 2025). These results confirm the efficiency of the stone column technology, in its traditional shape and with the current reinforcement improvements.

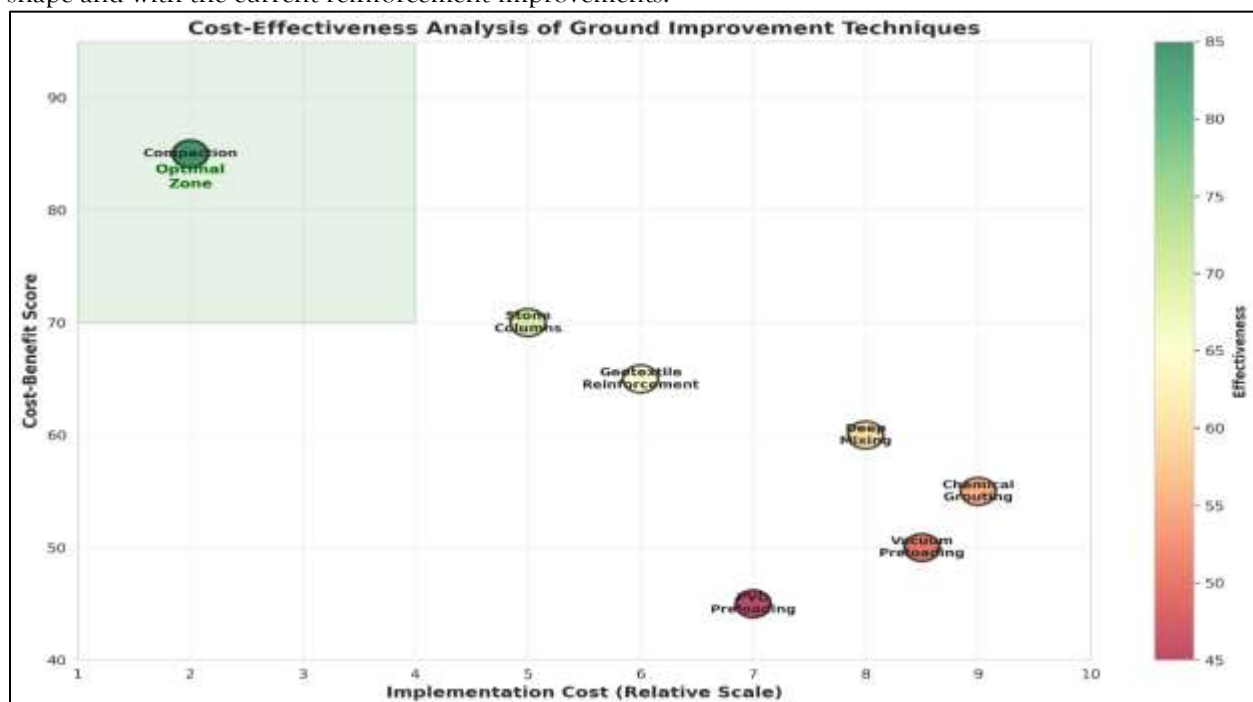


Figure 4 Cost-Effectiveness Analysis of Ground Improvement Techniques

Advanced Column Configurations and T-Shaped Deep Mixing

The latest technological advancements in the field of column-based ground improvement have brought with it the T-shaped and modified geometry that offers better performance as opposed to the traditional cylindrical columns. Relative seismic analysis proves that T-shaped deep cement mixing (TDM) columns show a better

performance in terms of settling by 89.95 per cent compared to conventional deep cement mixing (DCM) columns by 36.11 per cent (Boufarh et al., 2025). The TDM columns had 88.31% less settlement than the DCM columns under seismic loading at the embankment crest (Boufarh et al., 2025). Parametric analysis showed that the settlement was lower in columns spaced by less than 1.67 m, that is, the residue of 1.67 m and 0.0032 m produced 0.023 m settlement respectively in columns spaced by 1.67 m and 0.023 m (Boufarh et al., 2025). The results show that TDM columns feature a better seismic performance in terms of load transfer mechanisms and better soil-structure interactions (Boufarh et al., 2025). These sophisticated designs constitute the development of column-based ground improvement methods that give engineers more efficient measures in solving the problematic soil conditions, especially those that are seismically active. The benefits of the performance of advanced column geometries in both conventional and seismic loading environments are becoming more appealing to modern ground improvement projects.

Performance Evaluation and Design Considerations

Settlement Analysis and Bearing Capacity Assessment

To ascertain the effectiveness of ground improvement, the overall evaluation of the bearing capacity enhancement and the settlement reduction brought about by the treatment is to be done. The pre-improvement soils need to be outlined with a lot of care by conducting a wide site exploration consisting of boring, sampling, and lab tests to determine the baseline properties (Das, Islam and Datta, 2025). The post-improvement assessment using test excavations, laboratory analysis of enhanced soil samples and, in-situ analysis, gives information that is required to confirm that design goals have been met. The use of one-dimensional theory of consolidation is common in settlement analysis where the primary consolidation is estimated under loads (Cui et al., 2024). Finite element-based numerical modeling has been found to be very useful in settlement prediction and bearing capacity of enhanced ground systems. The extensive case study of embankment behaviour in soft ground shows that finite element analysis predicts the behaviour of consolidation and allows geotechnical parameters to be calibrated, and the properties of settlement and excess pore pressure back analysis predict the results of embankment model predictions and verifies them against the available data (Ramilo, Haxell and Cole, 2025). It was demonstrated that there was excellent consistency between the modelled and measured results and this indicates the efficacy of the approach adopted in surcharging. Plane strain two-dimensional and three-dimensional models with actual geometry, material behavior, staged construction cycles, and monitored performance data give detailed forecasts of the patterns of stresses and settlement (Tregub et al., 2025).

Monitoring and Adaptive Management Systems

The use of ground improvement often embraces monitoring programs to ensure that the design assumption is achieved, and also to allow adaptive management whenever field conditions are not according to the prediction. Tracking of settlement using predetermined benchmarks or more advanced settlement plates can be used to directly measure ground settlement during embankment construction, or at its installation stage after having been preloaded (Robinson, Thilakarathne and Thilakasiri, 2024). The use of piezometers at different depths in pore pressure monitoring delivers information on the progress of consolidation and also allows one to determine whether excess pore pressures are being eliminated at a rate that is similar to that predicted by the design. The observational methodology was used to cope with geotechnical uncertainty, as it is based on observed data and improves the numerical models to make construction decisions (Ramilo, Haxell and Cole, 2025). One area that continues to grow is the use of real-time monitoring systems on large projects, and automated data collection, telemetric transmission and computer analysis allow detection of anomalies early and trigger adaptation in real-time (Das, Islam and Datta, 2025). A number of monitoring systems were also put in place to observe the conduct of embankment systems as they were put in place to ensure that the necessary data to authenticate design methods and ensure the viability of mitigating mechanisms was attained (Kartawiria et al., 2025). Data of instrumentation measured during and after construction supported the strategy and proved the usefulness of mitigation in complicated soft soil settings

(Das, Islam and Datta, 2025). In case of a project that has a high level of contractual and environmental interest, detailed monitoring will offer the necessary records of proper building and risk management.

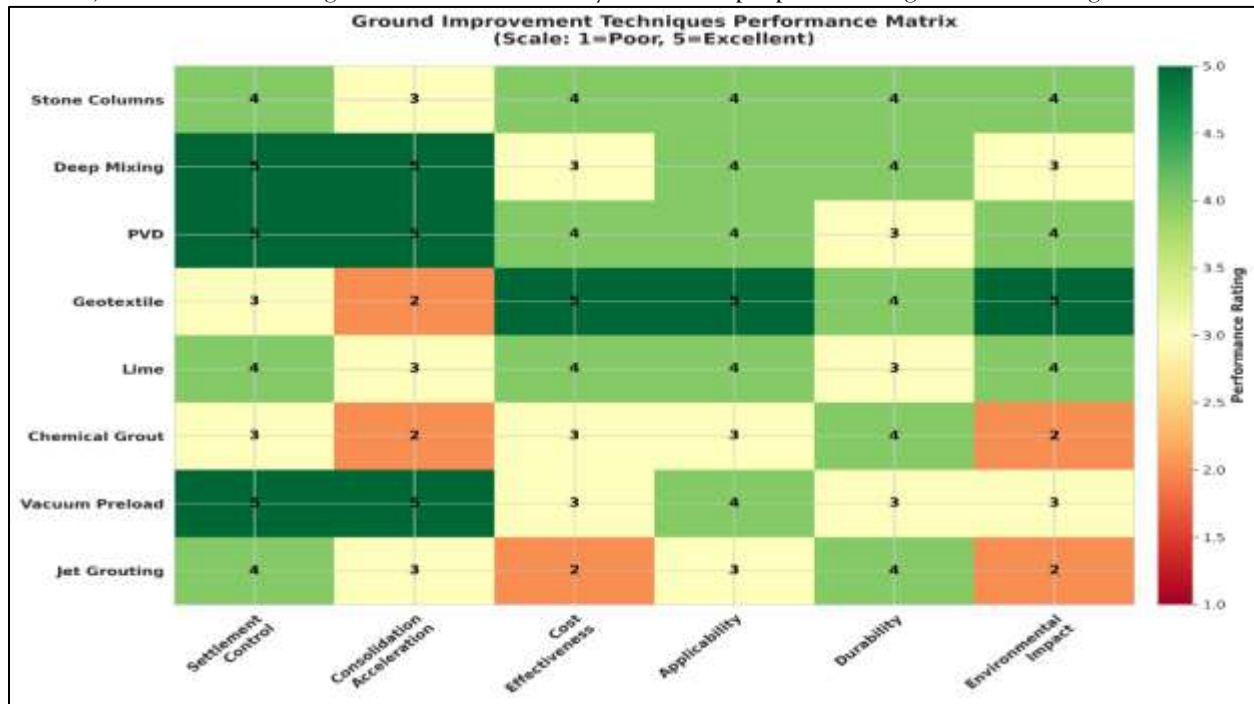


Figure 5 Ground Improvement Techniques Performance Matrix (Scale: 1=Poor, 5=Excellent)

Design Methodology and Effectiveness Metrics

Ground improvement systems design involves a combination of geotechnical analysis with economic and practical aspects with the aim of coming up with cost-effective solutions that deem to be relevant to the project needs. The choice of methods of improvement of the ground is based on various factors such as depth and an aerial area of poor ground, sensitivity of the project to settlement, construction schedule, availability of materials and equipment, and regulatory or environmental limitations (Husaini et al., 2025). In the case of embankments on soft soil, the design choices usually comprise trade-offs involving the height of the embankment that can be built with a reasonable safety margin against the size of ground improvement necessary to attain a reasonable settlement behavior. A comparison study between deep mixing and stone column proves the Deep Mixing Column to be more helpful in reducing settlement, its effectiveness is 38%-80 and Stone column is more helpful in reducing the time taken to consolidate, its effectiveness is 53%-99 (Hamdhan and Raasyid, 2025). This comparative study helps engineers to adopt the best techniques depending on the priorities in the project. The factors of safety used in the design of ground improvement are usually between 1.3 and 1.5 to ultimate limit states and are supplemented by serviceability issues such as restrictions on settlement magnitude and preferential settlement. The studies investigating the embankment construction on soft soils show the need to consider adaptive evidence-based strategies to consider the intricate soil environments (Das, Islam and Datta, 2025). Adaptive management of ground improvement processes is now possible through real-time monitoring systems, enabling adjustments based on field performance. Recent research extends this concept through construction-phase digital twin frameworks, where integrated data streams and predictive models support proactive quality assurance and element-level decision-making in infrastructure projects [Islam et al., 2026].

Case Studies and Practical Applications

Highway and Embankment Projects

Embankments on highways and transportation systems built on loose soils are one of the key areas of application of ground improvement methods, and the existing practices have proven successful in a wide range of geological and climate conditions. The Semarang-Demak Toll Road project in Indonesia is an

important case study in which the main problem was the construction of embankments on soft soil layers with a thickness of up to 40 meters (Kartawiria et al., 2025). Without ground improvement methods, very soft soil with undrained shear strength of about 6.5kPa would bear only a critical embankment height of about 3 meters (Kartawiria et al., 2025). To attain an embankment height of 6 meters, a hybrid system that has been developed with bamboo mattresses, high-strength woven geotextile, PVD and staged embankment construction was adopted and the analysis of the finite elements showed better construction performance and safety factor of 1.25 and 1.55 respectively (Kartawiria et al., 2025). The construction of highways embankment using ground improvement shows that the construction of stable embankment construction can be achieved by using preloading with prefabricated vertical drains that does not entail excavation and replacement of large deposits of soft soils. The studies of the numerical modeling of road embankment on soft soils prove that the preload technique based on the filtering embankment with vertical drains reinforces soft soils and enhances the bearing capacity of the foundation in a relatively small time frame (Tregub et al., 2025). Highway embankment stabilization by deep mixing has been applied in Asian countries which have shown to be able to deal with challenges such as soft clay with the presence of organic layers in it (Thang, 2023). Research on embankment stability on soft soil deposits has demonstrated that observational approach techniques such as construction control diagrams and charts offer useful mechanisms of determining and managing embankment stability (Robinson, Thilakarathne and Thilakasiri, 2024). These monitoring schemes concentrate on fill height, sideways movement, and vertical settlement as the monitored critical parameters that can be used to measure embankment performance in real time. According to the Colombo-Katunayake Expressway project where stone columns installation was used as one of the primary ground improvement techniques, it proves the success of such techniques in determining successful configurations and failures (Robinson, Thilakarathne and Thilakasiri, 2024).

Urban Development and Building Foundations

The developments of urban regions that are possessing the soft soil have led to new innovation in the ground improvement methods that can be used within the limited building site conditions. The buildings that are constructed on weak soil usually experience issues of the uncontrollable settlement and critical bearing capacity (Thageel and Shaia, 2024). Tall buildings, especially those that have high rise, should endeavor to consider the settlement difference between columns to avoid structural damage and therefore careful design of ground improvement is required so that the improvement is homogeneous in the building footprints. The use of geosynthetic-based methods in the construction of urban buildings is also shown through ground improvement technique, which uses geosynthetics as a form of reinforcement on the soft ground (Haritha and Krishnamurthy, 2023). Modulus of subgrade reaction test and plate load test were also tested on a refined ground to determine the quality of improvement (Haritha and Krishnamurthy, 2023). Examples of buildings built over enhanced soft soils, using suitably designed systems can show that acceptable settlement can be obtained even when post-construction settlements are within stated limits of tolerance. The study of design of embankments on soft ground conditions, as in the case of the Dohazari Coxs Bazar Railway Project, shows that intensive site investigations indicate that there are layers of clay soil with a specific bearing capacity, and that special methods should be applied, which include PVDs, staged construction, preloading, and high strength geotextiles (Das, Islam and Datta, 2025). The method and the measures used to mitigate flooding were effective as evidenced by instrumentation data taken during and post construction (Das, Islam and Datta, 2025).

Specialized Applications and Environmental Considerations

The enhancement of the specialized environment on the ground poses special challenges that need specific solutions. The enhancement of the condition of the soft grounds in the swampy regions of South Kalimantan has shown that the preloading technology using Prefabricated Vertical Drain (PVD) and Vacuum Preloading can mitigate land subsidence and hasten the process of consolidation, where the preloading technique with PVD has proven to be most effective as it is able to reduce the settlement rate by 60 percent and speed up the process of consolidation 4.2 times faster than without the implementation of any preloading technique (Rahayu, Norfajriati and Octarin This use of problematic swamp soils illustrates how ground improvement methods can be employed in problematic areas. The use of PVDs in Container Yard Area of Sunda Kelapa

Port, Jakarta shows marine uses of ground improvement methods (Raines et al., 2024). The site has deep, soft and low shear strength, high compressibility clay deposits which are under great risks of settlement under structural loads. The researchers assessed the PVD installation performances in different depths and determined that full-depth installation of PVD always yielded the best settlement and was better in promoting the consolidation of the entire compressible layer (Raines et al., 2024). PVD combination preloading methods of ground improvement have shown to be applied to particular industrial projects. The intended PVD of the Akatara Gas Plant Facility undertaking in Jambi comprised non-woven PVD in different size specification and installation designs (Afkarina et al., 2024). Depending on the analysis results, soil preloading was also used in combination with the vacuum preloading in order to overcome certain site conditions (Afkarina et al., 2024). The results of the analysis established that the best PVD installation distance and pattern were 110 cm with a square pattern (Afkarina et al., 2024).

Emerging Technologies and Future Directions

Ground Improvement Technique	Settlement Reduction (%)	Consolidation Acceleration (%)	Cost per m ²	Typical Treatment Depth (m)	Applicability in Soft Clays
Preloading	60-75	40-60	15-30	5-20	Excellent
PVD + Preloading	75-90	70-90	25-40	5-30	Excellent
Stone Columns	30-50	20-40	40-70	10-20	Good
Deep Mixing	60-80	50-70	35-60	10-60	Very Good
Lime Stabilization	50-70	30-50	20-35	Surface	Good
Cement Stabilization	70-85	40-60	25-45	Surface	Very Good
Vacuum Preloading	70-85	65-85	30-50	10-25	Very Good
Geotextile Reinforcement	20-40	10-25	10-25	Variable	Fair

Table 1: Comparative Performance Metrics of Ground Improvement Techniques

Electrokinetic stabilization is a new technology in the ground improvement of soils which are inappropriate to the traditional methods of stabilization. The assessment of the electro-osmotic stabilization of soft clay in the laboratory indicates that the use of electro-osmosis has gained momentum in geotechnical engineering as a new technique in situations where conventional geotechnical techniques of ground improvement are inapplicable (Jeyakanthan, Gnanendran and Lo, 2011). Electro-osmosis application in stabilizing soft clay presupposes the design of electro-osmotic testing equipment that can be used in the permeability and pore-water pressure measurements formed during the treatment (Jeyakanthan, Gnanendran and Lo, 2011). Effectiveness has been proven to be effective in numerous applications in the field; nevertheless, the engineers are still reluctant to employ these techniques because of the unpredictable impact of the electro-chemical changes (Jeyakanthan, Gnanendran and Lo, 2011). New environmental problems with the traditional plastic drains can be solved by the recent innovations in biodegradable vertical drains. The vertical drainage consolidation technique is very common in improving a soft ground where traditionally prefabricated plastic vertical drains (PPVDs) are used to enable the efficient discharge of the pore water (Yuan et al., 2024). In an

attempt to counter the existing environmental challenges caused by non-biodegradable PPVDs, natural prefabricated vertical drains (NPVDs) and prefabricated straw vertical drains (PSVDs) have come out as viable solutions (Yuan et al., 2024). Pilot testing demonstrates that NPVD and PSVD degradation do not have a significant impact on the process of soil consolidation, but they are beneficial to the environment (Yuan et al., 2024). The results indicate the promise of biodegradable drains as a sustainable source of soft ground improvement (Yuan et al., 2024).

The growing trend towards being more sustainable in construction and development of infrastructure has fuelled the technological advances in ground improvement methods that reduce the amount of resources used and their impact on the environment. The extensive literature analysis on geotechnical stabilization methods has shown that conventional methods of soil stabilization may fail miserably when viewed through the prism of long-term operation, environmental effects, and the versatility to work within the challenging locations (Bhagatkar and Lamba, 2024). The current practices that involve industrial by-products and new biotechnological innovations such as the microbial-induced calcite precipitation can provide better sustainability (Bhagatkar and Lamba, 2024). The application of recycled materials to the ground improvement process proves that the following types of waste materials have been explored in terms of their effectiveness in developing geotechnical properties: industrial wastes (fly ash, cement kiln dust, blast furnace slag), construction and demolition wastes (recycled concrete and asphalt aggregates), and other waste materials (Elyiğit, 2025). Studying results show that such materials cause favorable shifts in the soil properties, including plasticity, strength, swelling potential, and permeability (Elyiğit, 2025). Moreover, the application of these materials has huge benefits in the environmental sustainability aspect, such as lowering the carbon footprint, preserving the natural resources and enhancing the waste management (Elyiğit, 2025).

CONCLUSION

Ground improvement techniques for soft soils have evolved substantially over recent decades, driven by advancing theoretical understanding, technological innovation, and accumulating performance data from completed projects. The comprehensive review of the most widely used techniques for soft soil improvement, including deep mixing, jet grouting, preloading, and vertical drains, demonstrates that each method has strengths and limitations, with a combination of techniques often yielding the best results depending on site-specific conditions. The diversity of available techniques mechanical methods including preloading and vibratory densification, chemical stabilization through cement and lime treatment, and inclusion-based approaches such as stone columns and deep mixing provides engineers with substantial flexibility in designing solutions appropriate to specific project requirements.

The integration of emerging technologies including real-time monitoring systems, numerical modeling capabilities, and digital platforms is transforming how ground improvement projects are planned and executed, enabling more efficient designs and adaptive management during construction. Simultaneously, sustainability imperatives are driving development of innovative techniques utilizing waste materials and minimizing resource consumption and environmental impact. The convergence of these trends—advancing technical capabilities and increasing sustainability emphasis—suggests that future ground improvement practice will emphasize optimized, site-specific solutions that achieve necessary engineering performance while minimizing environmental footprint and resource requirements.

Continued research addressing remaining knowledge gaps, particularly regarding long-term performance of combined or innovative techniques and mechanisms of interaction between improved ground and superimposed structures, will further enhance the capabilities and cost-effectiveness of ground improvement for soft soils. The extensive case study documentation from major projects implementing contemporary techniques provides valuable guidance for future applications, though each project's unique conditions require careful evaluation of lessons learned. For engineers and decision-makers involved in soft soil ground improvement, the contemporary toolkit of available techniques, supported by advancing analytical and monitoring capabilities, enables practical and economical solutions to what historically represented intractable geotechnical challenges.

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