International Journal of Engineering Research

Sirte University
Faculty of Engineering

Journal homepage: [Scientific Journals (su.edu.ly)](https://journals.su.edu.ly)

Soil Reinforcement to Support Building Foundations

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ARTICLE INFOR

Article history:

Received 25 Feb 2025

Revised 28 March 2025

Accepted 27 April 2025

Available online

15 May 2025

ABSTRACT

Soil reinforcement is a crucial technique in geotechnical engineering to improve the strength, stability, and load-bearing capacity of soil for supporting building foundations. Weak or loose soil can lead to structural failures, differential settlements, and long-term instability, necessitating the use of various reinforcement methods such as geotextiles, geogrids, soil nailing, and deep soil mixing. This research explores the effectiveness of different soil reinforcement techniques in enhancing foundation performance, analyzing their impact on soil strength, settlement reduction, and overall structural integrity. Through field studies and laboratory testing, the study evaluates the suitability of reinforcement methods for different soil types and load conditions. The findings provide valuable insights into cost-effective and sustainable soil stabilization techniques, offering practical recommendations for engineers and builders to optimize foundation design and construction. This research contributes to the development of resilient and durable building foundations, minimizing risks associated with poor soil conditions and ensuring long-term structural safety.

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Keywords: *Soil reinforcement, Geotechnical engineering, Foundation performance, Stability, Structural safety*

1. Introduction

The growing need for reliable and long-lasting infrastructure has drawn attention to soil reinforcing techniques in geotechnical engineering, especially important for improving slope stability, increasing bearing capacity, and reducing soil settlement in foundation systems, retaining walls, and roads. Due to excessive settlement, loss of bearing capacity, and structural instability, weak soil conditions present serious design issues for foundations. Numerous soil reinforcement techniques, each suited to a particular soil type and construction need, have been developed to address these problems. Environmental variables, loading circumstances, and soil composition all affect how effective these techniques are (Indraratna et al., 2023). The usage of geotextile is among the most popular methods for soil reinforcement. by enhancing tensile strength and decreasing water permeability, geotextiles synthetic fabric materials improve soil stability (Basu et al., 2019). These materials improve foundation performance and avoid excessive settling, especially in sandy and soft clay soils. Additionally, geotextiles improve soil behavior under load situations by facilitating drainage and lowering pore water pressure (Zhou et al., 2023).

Figure 1. Foundation Soil Reinforcement

Source: Geouzol (2024)

Figure 1. shows construction activities involving heavy equipment for pile foundation work. In order to provide structural support, piles are being actively driven into the earth using a Liebherr LR 100 crane-type pile driver (Geouzol, 2024). This procedure is used to strengthen a building's or infrastructure's foundation, especially in places with soft or unstable soil. In order to reach a stable, load-bearing soil layer, the piling

machinery drives or presses piles into the earth. This guarantees a solid and dependable foundation for the building (Geouzol, 2024). The surrounding environment shows muddy and wet areas, indicating that this location may have soil conditions that require deep foundations. In addition, there are workers wearing personal protective equipment (PPE), indicating that this project pays attention to work safety aspects.

The mechanical characteristics of the underlying soil have a significant impact on the stability of building foundations. Differential settlement, foundation collapses, and structural damage are frequently caused by weak or loose soils. To increase soil carrying capacity and lower settlement concerns, soil reinforcement techniques such geosynthetics, soil stabilization, and deep foundation systems have been widely used (Rad et al., 2024). These techniques guarantee that even poor soils may efficiently sustain heavy structural loads. In urban settings, where land is scarce and high-rise buildings need improved ground stability, soil reinforcement is especially important (Verma et al., 2021).

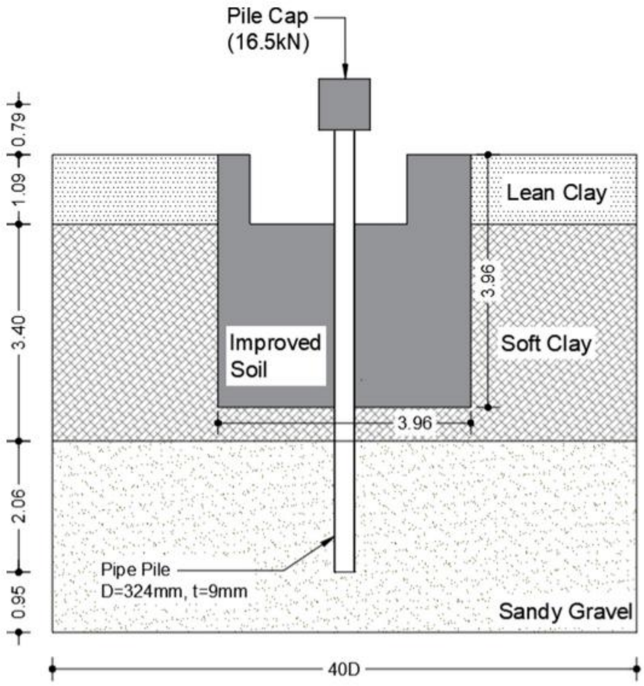


Figure 2. Geotechnical Profile and Pile Foundation Plan

Source: Hussein & El Naggar (2022)

Figure 2. is a geotechnical diagram showing soil layers and the plan for installing gravel piles. Gravel piles with a diameter of 800 mm; 2.1x2.5 m. This diagram is essential for building planning and civil engineering since it helps choose

the right kind of foundation depending on the soil. Engineers can assess soil stability and choose the best foundation technique since different soil layers are depicted with unique patterns. Construction experts may choose the best foundation technique to guarantee long-term stability and structural integrity by being aware of these elements. The areas outlined in red indicate zones that require additional reinforcement. This data is important in construction projects such as bridges, high-rise buildings, or highways to ensure adequate soil bearing capacity.

Geosynthetics such as geogrids, geotextiles, and geomembranes, are among the most widely used techniques for reinforcing soil. These substances avoid excessive settlement by improving the soil's tensile strength and more evenly distributing the load. While geotextiles are favored for drainage and filtration applications, geogrids are frequently utilized in the construction of roads and embankments. When compared to unreinforced soils, geosynthetic-reinforced soils have noticeably higher shear strength and load-bearing capability (Wu et al., 2019). Geogrids are yet another popular reinforcement material, particularly for strengthening weak soils' mechanical qualities. Because these polymer-based grids interlock with soil particles, they improve soil strength by distributing load and adding stability. When building on loose or weak soils, geogrid-reinforced foundations are a good option because of their higher bearing capacity and less settlement (Li et al., 2024).

Soil stabilization is another crucial strategy that uses mechanical or chemical methods to enhance the soil's engineering qualities. Stabilizers like lime, cement, and fly ash are frequently used to increase the cohesiveness and resilience of soil (Renjith et al., 2021). Stabilizing cement is especially useful for boosting soil strength in expansive clays, which are prone to volume shifts because of moisture variations. Stabilizers based on polymers have also become a viable substitute, providing advantages for the environment and enhancing soil quality (Barman & Dash, 2022). Steel bars or tendons are inserted into pre-drilled holes and grouted to strengthen in-situ soil, enhancing soil stability and cohesiveness (Cola et al., 2019). This technique ensures that structures constructed on reinforced soil retain their long-term integrity and is especially helpful for deep foundation support and slope stabilization. Soil nailing has been shown to be successful in minimizing retaining structure deformation and preventing landslides (Benayoun et al., 2021).

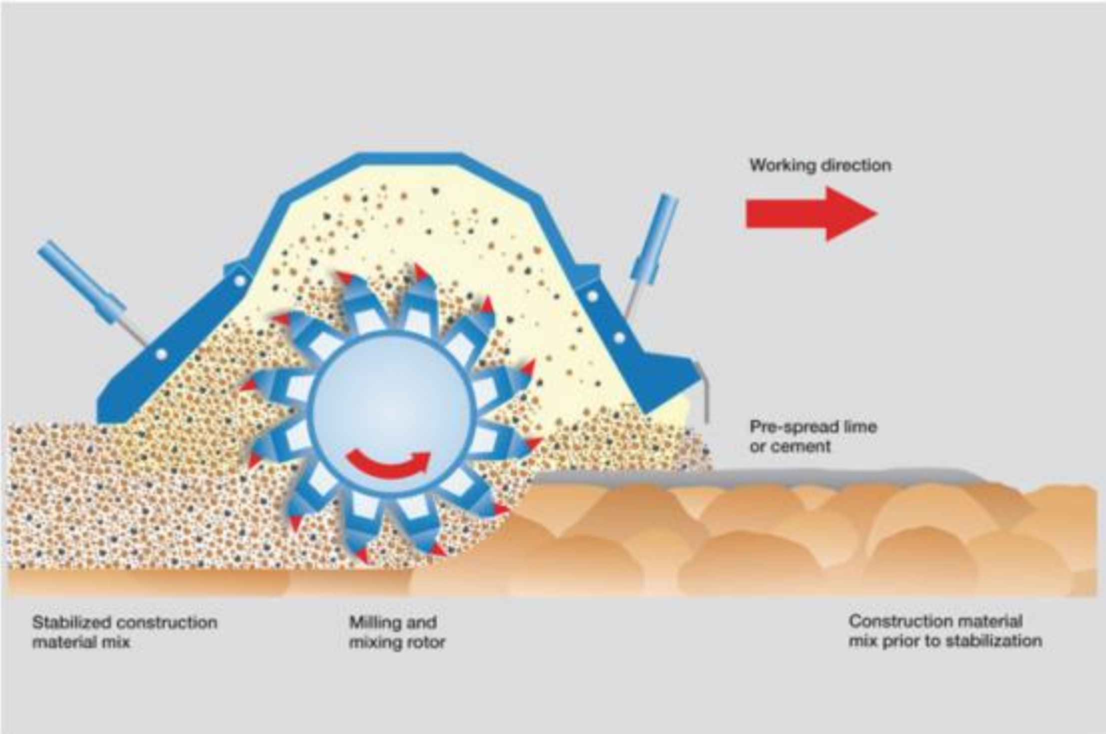


Figure 3. Soil Stabilization Process

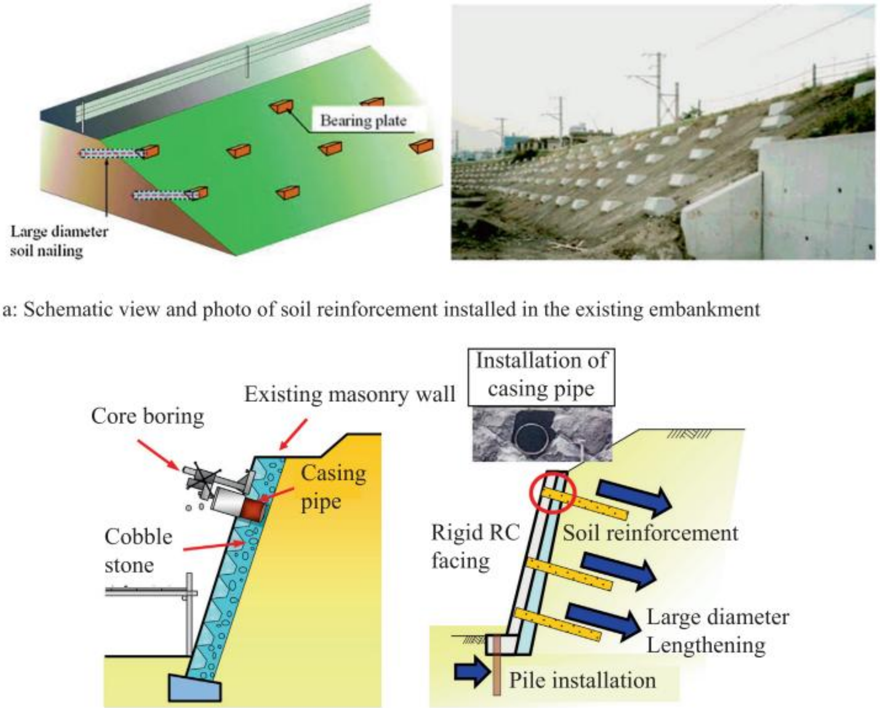
Source: Amhadi & Assaf (2019)

The process of stabilizing the soil involves mixing or distributing the stabilizing ingredients over the components that require stability. As seen in Figure 3, the additives are typically blended into the soil until the required qualities are obtained. After that, the road or foundation materials are installed. Depending on the required soils and additives, this procedure may change. Furthermore, it should be mentioned that the stabilizing elements' organic components, sulfates, sulfides, and carbon dioxide may contribute to the treated soil's unexpected or unwanted characteristics (Amhadi & Assaf, 2019).

A sophisticated technique forsoil reinforcing is deep soil mixing, which combines cementitious materials with soil to enhance its mechanical qualities. Shear strength and load-bearing capacity can be increased with this technique, which is especially helpful for soft and readily compacted soils. When soil conditions are extremely compacted, deep soil mixing decreases settlement and increases overall foundation stability (Barman et al., 2022). One of the biggest problems with soil reinforcement is figuring out which technique is best for a certain site. When applying reinforcing techniques, engineers must consider the typeof soil, load distribution, environmental impact, and cost-effectiveness. Because of its long-term economic savings and environmental advantages, sustainable methods like using recycled materials and bio-based reinforcing agents have grown in prominence (Moshood et al., 2021). Rock columns and pile foundations are two common deep foundation techniques used to reinforce poor soils. To lower the chance of settling, pile foundations shift structural loads to deeper and more capable soil layers (Basack & Purkayastha, 2021). Rock columns are appropriate for liquefaction-prone areas because they enhance soil drainage and shear strength. For high-rise structures in soft soil conditions, the combination of deep foundation techniques and geosynthetics can yield superior reinforcement outcomes (Castro & Sagaseta, 2021).

Field tests and finite element modeling have shown that reinforced soil foundations are successful under a range of loading scenarios. Engineers can forecast soil behavior and optimize reinforcement design with the aid of sophisticated computational models (Xu et al., 2021). The durability and dependability of reinforced soil systems are guaranteed by extensive field testing, which validates these models and offers insights into long-term performance. Recent advances in machine learning and artificial intelligence have significantly enhanced the prediction of soil reinforcement, lowering design uncertainty (Davies et al., 2025). Soil reinforcement is crucial for lowering seismic risks in earthquake-prone areas. To increase soil stability during seismic occurrences, liquefaction-resistant reinforcing techniques including dynamic and vibration compaction have been frequently used (Zhou et al., 2024). It has also been demonstrated that geosynthetic-reinforced soil walls are capable of withstanding earthquake-induced lateral ground motion. Earthquake resistance is increased by adding energy-absorbing materials to the reinforced soil layer (Yildirim et al., 2024).

Reducing environmental effects while preserving excellent structural performance is the major goal of sustainable soil reinforcing techniques. Utilizing recycled materials for soil stabilization, such as waste plastic and shredded rubber, has gained interest as an eco-friendly substitute, with studies indicating their ability to improve load-bearing capacity and reduce settlement in weak soils. Furthermore, biotechnology methods like vegetation-based reinforcement enhance soil stability while contributing to erosion control and carbon sequestration, aligning with global sustainability goals. This strategy supports ecologically conscious building methods by reducing landfill waste and lowering carbon emissions compared to traditional cement-based stabilization. With continued research and development, the integration of soil reinforcement technologies into contemporary construction is expanding. Advancements in geopolymers and nanomaterials offer promising alternatives, with geopolymers reducing CO_2 emissions by up to 80% compared to Portland cement, while nanomaterials improve soil strength with minimal material use (Madirisha et al., 2024).



b: Schematic views of soil reinforcement and core boring as the preparatory work for aseismic reinforcement of the existing retaining wall

Figure 4. Soil Reinforcement

Source: Nakajima et al. (2022)

Large-diameter soil reinforcement (LDS), as seen in Fig. 4a, is a technique for creating soil reinforcement using mechanical mixing that has a diameter of 300 to 400 mm. Since a greater tensile resistance is anticipated due to the soil reinforcement's vast surface area within the embankment, its length and number might be decreased in comparison to the standard soil reinforcement technique. However, the stable, stiff soil that is occasionally found behind the retaining wall in front of the cut slope cannot be reinforced with this equipment mixing soil reinforcement, nor can it be applied to soils that include big gravel particles or rock mass. Furthermore, as shown schematically in Fig. 4b, when LDS is used to reinforce a retaining wall, the wall facing's core boring and the installation of the casing pipe must be completed before building the LDS, which requires a significant amount of effort (Nakajima et al., 2022).

Soil reinforcement behavior has been better understood thanks to recent developments in field testing and numerical modeling. Using finite element modeling, engineers may optimize designs and simulate several reinforcing scenarios prior to construction. Experimental research has confirmed the efficacy of several reinforcement techniques, offering trustworthy information for engineering applications. To guarantee the stability and longevity of building foundations, soil fortification is essential. Through the integration of sustainable practices and modern reinforcing techniques, engineers may improve soil performance, reduce construction risks, and create robust infrastructure for the future (Malik et al., 2023).

LITERATURE REVIEW

Geosynthetic Reinforcement

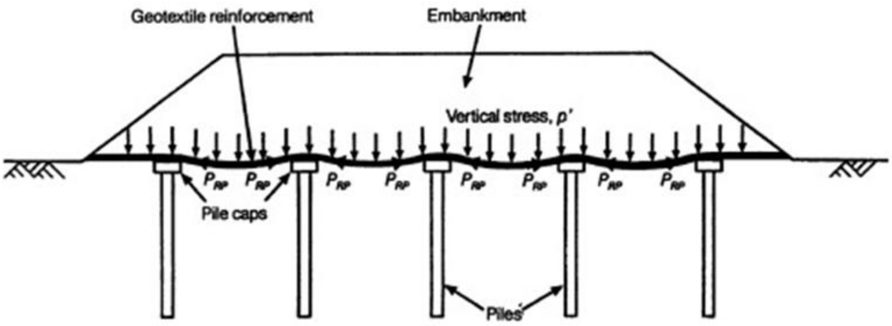


Figure 5. The Role of Geosynthetic Reinforcement in Transferring the Vertical Embankment Loading onto The Pile Caps

Source: Lawson (1992)

Geosynthetic reinforcement is sometimes required to provide additional stability in the construction of embankment on soft soil. However, it can only help stability to a certain extent. Geosynthetic reinforcement cannot reduce pore water pressure during fill placement and, thus, settlement is still a big issue. In Europe, it is common to combine pile with a cap underneath the geosynthetic to carry the load of embankment by the axial capacity of the pile. The geosynthetic reinforcement carries part of the embankment load so that the soft soil stresses are reduced (Lawson, 1992). Adding synthetic materials to soil structures, like geotextiles, geogrids, and geocells, to enhance their mechanical qualities is known as geosynthetic reinforcement. In civil engineering applications such as foundation systems, embankments, and retaining walls, this method is frequently employed to increase the strength, stability, and load-bearing capacity of soil. To create more effective and cost-effective foundation designs, geosynthetic reinforcement can dramatically raise soil bearing capacity and decrease settlement (Al-Salamy et al., 2024).

The type of geosynthetic material used, the nature of the site, and the application all influence the success of geosynthetic reinforcement. Granular soils are frequently reinforced with geogrids, which increase overall stability by limiting lateral soil movement through their tensile strength. Three-dimensional geosynthetics called geocells have been demonstrated to enhance subgrade performance under repeated loading scenarios, which makes them appropriate for use in railroads and highways. Performance in reinforcing applications has improved because of developments in geosynthetic materials, such as the creation of new polymer blends. When compared to conventional materials like high-density polyethylene, novel polymeric alloy-based geosynthetics have greater tensile strength and stiffness, which improves long-term performance and durability. Because of these advancements, geosynthetic reinforcement is now used in more important infrastructure projects, such as high retaining walls and heavy-duty pavements (Tutumluer et al., 2024).

Soil Nailing

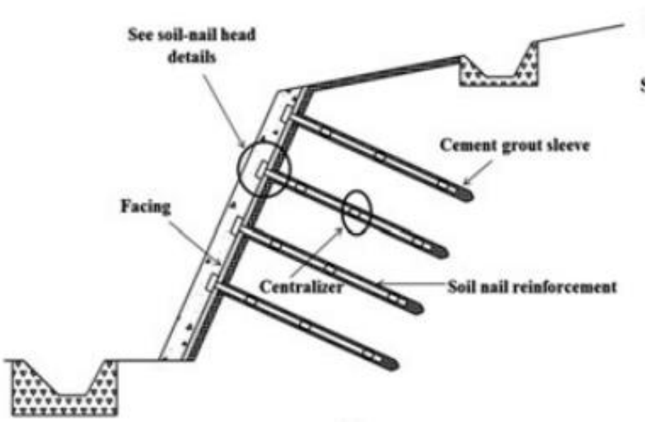


Figure 6. Soil Nailing Technique

Source : Sharma et al. (2019)

Soil nailing is a geotechnical method used to reinforce the existing soil mass and stabilize slopes, excavations, and retaining walls. Using this technique, the soil's stability and load-bearing ability are increased by introducing thin, usually steel, reinforcing components known as "nails" into the ground. Typically, the procedure entails drilling holes into the excavation face or slope, putting steel bars in, and grouting them in place to create a composite mass that is immobile. To give the surface more stability and stop erosion, a facing system is added, usually made of shotcrete or precast panels. The soil nailing technique, which uses in-situ soil reinforcing to improve stability, is a trailblazing approach to slope reinforcement construction. The basic idea is to create a composite body by installing reinforcing mesh on the slope surface, putting concrete on top, and putting thin rebars into the ground. Like a gravity retaining wall, this construction rigidly connects reinforced rods to the soil (Al-Hamdan & Kavazanjian, 2019).

Soil nailing's history begins in France in the 1970s, when technique was initially applied to stabilize railroad cuttings. Since then, the method has developed and become widely used throughout the world because of its efficiency and affordability. Because it takes less area and smaller equipment than typical retaining structures, soil nailing is especially beneficial in urban settings with limited access. It is a preferred option in many geotechnical applications since it also makes it possible to stabilize existing slopes without requiring significant excavation. To guarantee stability and function, a soil nail wall's design must considera number ofkey factors. The assessment of soil characteristics, the choice of appropriate materials, the calculation of nail length and spacing, and the examination of environmental elements and external loads are all important considerations. To forecast how the attached soil mass would behave under different loading situations, sophisticated analysis techniques like limit equilibrium and numerical modeling are frequently used. To control groundwater and avoid hydrostatic pressures that can jeopardize the integrity of the system, proper drainage facilities are also crucial (Elahi et al., 2022).

Soil nail wall construction is usually done in a top-down manner. A portion of the slope or wall face must first be excavated, and then holes must be drilled at precise angles and positions. After that, steel bars are put into these holes and grouted to cement them to the soil. To give the exposed surface structural strength and weather resistance, a facing material is put after the nails are installed. Until the required height or depth is reached, this process is repeated in phases. Throughout the building process, quality control procedures are crucial to guaranteeing adherence to design standards. These procedures include load testing nails and tracking wall motions. Compared to conventional earth retention techniques, soil nailing has a number of benefits. In general, it is quicker and less expensive to implement, especially when the usage of bulkier systems is restricted by existing structures or space limitations. The method is adaptable and can be used with cohesive soils, granular materials, and worn rock, among other soil types and circumstances. Its use, however, can be restricted in regions with high groundwater levels, extremely caustic conditions, or extremely soft soils. In these situations, further precautions would be required to guarantee long-term performance, such as improved drainage systems or corrosion protection for nails (Jyothi & Krishna, 2022).

Deep Soil Mixing

Deep Soil Mixing (DSM) is a sophisticated ground improvement method that mechanically blends poor soils with cementitious binders to improve their engineering qualities. By mixing in-situ soils with binders like cement or lime using specialist equipment, soil-cement columns with greater strength and decreased compressibility are created. A useful technique for enhancing soil stability in a variety of building projects, deep soil mixing is especially efficient at treating soft clays, silts, and loose sands. Inserting a mixing tool into the ground to the appropriate depth is the first step in the deep soil mixing procedure. The tool ensures complete mixing to produce a uniform soil-binder mixture by simultaneously injecting the binder and shearing the soil as it moves forward. This combination solidifies into columns with decreased permeability and increased load-bearing capacity after curing. Depending on the needs of the project, these columns' diameter and depth can be changed; normally, they range from 0.6 to 2.4 meters in diameter and can reach depths of up to fiftymeters (Huylenbroeck et al., 2021).

Increased bearing capacity, settlement management, and liquefaction mitigation are just a few benefits of deep soil mixing. It is also an effective way to stabilize contaminated soils by immobilizing contaminants and to build cut-off barriers to regulate groundwater movement. The method is adaptable and suitable for a variety of soil types and project applications in both onshore and offshore settings. Compared to conventional excavation techniques, deep soil mixing has a smaller environmental impact due to its little soil displacement and decreased spoil creation. Furthermore, as deep soil mixing frequently replaces the requirement for more costly deep foundation systems, it can be an affordable alternative. Due to the process's relative speed, construction timetables and project expenses are shortened.

In DSM projects, quality control entails both real-time monitoring of mixing parameters during installation and laboratory testing prior to construction to identify the best binder types and mix ratios. To make sure the ground improvement satisfies the required design standards, post-construction verification may involve coring the treated columns to evaluate strength and uniformity (Pan et al., 2020).

Vibro Stone Columns

The process of creating dense aggregate columns inside the soil to increase its load-bearing capacity and decrease settling is called vibro stone columns, or vibro replacement. Weak or unstable soils can be strengthened with this technique, which makes them ideal for sustaining a variety of constructions. Inserting a vibrating probe into the ground to the required depth is the first step in the procedure. Depending on the exact technique used, repurposed concrete or crushed stone is added to the probe's tip or through the ground once it has reached the desired depth. Following that, the vibrator is gradually raised and lowered, compacting the aggregate in layers until a dense column is created from the bottom to the top. This technique not only reinforces the soil but also densifies surrounding granular soils, thereby increasing overall stability. Vibro stone columns can be installed using either the dry bottom-feed or wet top-feed techniques. With the help of water jets, the vibrator breaks through the soil in the wet top-feed method, forming a gap around the probe into which surface aggregate is poured. On the other hand, by sending the aggregate straight to the vibrator's tip via an attached feed pipe, the dry bottom-feed method does not require water and is therefore better suited for specific soil types. A number of variables, including soil type, project specifications, and environmental concerns, influence which of these approaches is best (Wu et al., 2023).

Increased bearing capacity, decreased settlement, and decreased liquefaction potential in seismically active locations are just a few benefits of using vibro stone columns. One significant benefit is the enhanced bearing capacity, which lowers the chance of foundation collapse by assisting in the transmission of structural loads to deeper, more stable soil layers. Furthermore, by densifying the surrounding soil, vibro stone columns considerably lower settling and provide long-term stability. The reduction of liquefaction danger in seismically active places is another important benefit (Shirazi et al., 2020).

Structures can be sustained on better terrain without the need for deep foundations by using these columns to reinforce the soil, which lowers costs and speeds up construction. Furthermore, this method is adaptable to a variety of soil types and project kinds, including big industrial complexes and residential buildings. Utilizing real-time monitoring devices that track variables like lift rates, vibration frequency, and depth helps ensure quality throughout the installation of vibro stone columns. Operators can make instant adjustments to guarantee adherence to design standards thanks to the recording and display of this data. This kind of monitoring guarantees the ground improvement process's consistency and dependability, resulting in safer and more robust foundations for a range of structures (Moghrabi et al., 2022).

Geocell Confinement Systems

Geocell confinement systems, also known as cellular confinement systems (CCS), are advanced geosynthetic products designed to enhance soil stability and improve the performance of infill materials. These systems, which are made of high-density polyethylene (HDPE), expand on-site to create a three-dimensional honeycomb-like structure. This arrangement prevents lateral movement and increases the infill's load-bearing capability by confining and reinforcing materials like soil, sand, or gravel within its cells. In applications where environmental integration is sought, the perforated cell walls facilitate water movement, which encourages drainage and vegetation growth. The building of retaining walls, channel protection, slope reinforcement, and base stabilization are the main uses for geocell confinement systems. Geocells in base stabilization disperse applied loads over a larger area, lowering subgrade soil stress and enabling the use of recycled or locally accessible materials as infill, which lowers construction costs and has a less negative environmental impact. By stabilizing the infill material, geocells for slope reinforcement provide a barrier against erosion brought on by wave action or water runoff. The cells can be filled with concrete, vegetated soil, or angular rock, depending on the needs of the site, to produce the intended stabilizing and aesthetic results (Kim et al., 2025).

Geocell devices are used on slopes and channels in channel protection applications to offset different flow velocities. With the right anchoring and infill materials chosen according to the channel's properties, they can be installed straight on the slope. Concrete, vegetated soil, and angular rock are among the options; each offers varying degrees of environmental integration and protection. Geocells provide a visually appealing, economical, and labor-efficient option for retaining walls. Custom-made to the necessary proportions, the flexible HDPE panels are simple to attach around pipes, curves, and other structures. A green wall solution that blends in perfectly with the surroundings can be achieved by stacking panels to create vertical walls or stair-stepping them to accommodate vegetation. The U.S. Army Corps of Engineers began developing geocell technology in the late 1970s to build roadways over soft ground. To create a rectangular, extensible honeycomb structure that could withstand enormous loads and resist erosion, they fused plastic strips together. Since then, earth retention, erosion management, and load support are only a few of the civil engineering problems that geocell systems have developed into adaptable solutions for (Biswas & Krishna, 2017).

METHODOLOGY

This research investigates the effectiveness of various soil reinforcement techniques in enhancing foundation performance by analyzing their impact on soil strength, settlement reduction, and overall structural integrity. The study employs both field studies and laboratory testing to evaluate the suitability of reinforcement methods for different soil types and load conditions. Field studies involve in-situ testing of reinforced soil foundations to assess their performance under actual load conditions. Laboratory tests are conducted to determine the mechanical properties of reinforced soils, such as shear strength and compressibility. Advanced testing methods, including triaxial compression tests and consolidation tests, are utilized to evaluate the behavior of reinforced soils under various stress conditions. The research also incorporates numerical modeling to simulate the performance of reinforced soil foundations, providing a comprehensive understanding of their behavior.

RESULT AND DISCUSISON

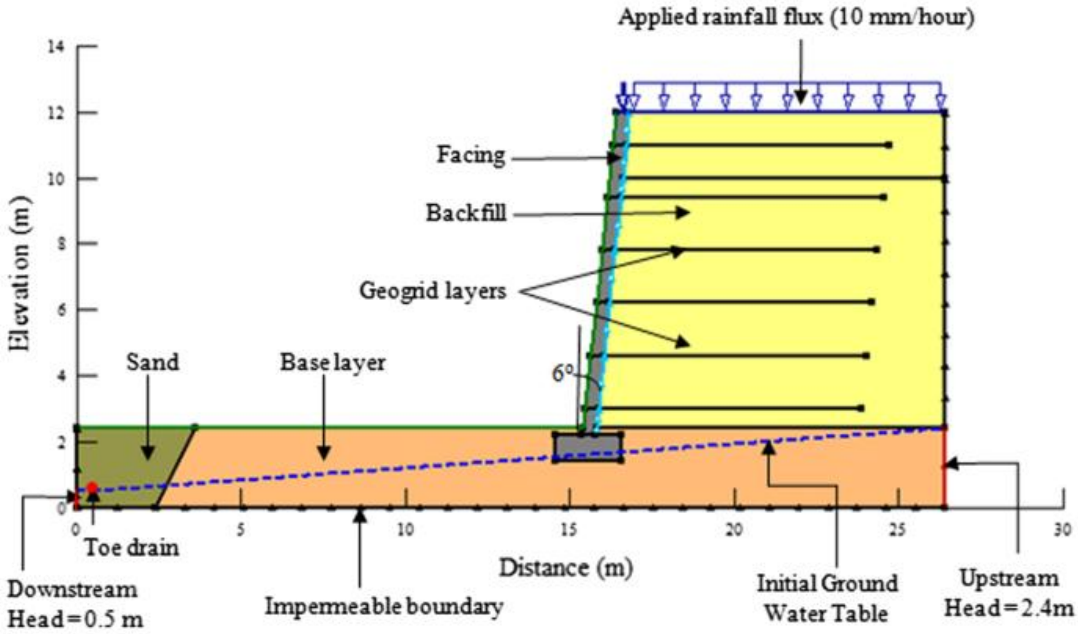


Figure 7. Soil Reinforcement Chart

Source : Jayanandan & Viswanadham (2020)

Figure 7 shows a technical illustration of the construction of a retaining wall, which functions to withstand soil pressure and prevent landslides, especially in areas with elevation differences. This structure consists of several main elements, such as AB Capstones, which function as a top layer to protect and beautify the appearance of the wall. AB Blocks form the main part of the wall and are reinforced by Wall Rock, a rock material that increases stability. Behind the wall is Retained Soil, which is the soil retained by this structure. In addition, AB Reinforcement Grid is used to provide additional reinforcement to the wall to withstand the thrust of the soil. Geogrid Length (L), a geotextile material or geogrid, is installed in the soil to increase stability by increasing the grip. At the bottom, there is Toe Drain, which functions as a drainage system to drain water and prevent the accumulation of hydrostatic pressure that can weaken the structure. This retaining wall is often used in road construction projects, hillsides, and other development areas that require soil stability.

Soil reinforcement is an important engineering practice that increases the strength and stability of soil to support building foundations. Various techniques, including geosynthetics, deep mixing methods, and soil stabilization with cement or lime, have been explored to increase the load-bearing capacity and reduce settlement problems. According to Al-Aghbari et al., (2018), geogrid reinforcement significantly increases the shear strength of soil, reduces differential settlement, and improves the overall stability of foundations. The efficiency of geosynthetics in weak soils, especially in expansive clay conditions where foundation performance is critical. According to Li et al., (2024) one of the main challenges in foundation engineering is the variability of soil properties, which requires site-specific reinforcement solutions. Cement and lime stabilization effectively increases the compressive strength of soft clay soils. The treated soil exhibits better stiffness and reduced water content, making it suitable for supporting large structural loads. In addition, the mechanical properties of stabilized soils depend on the drying time and the type of binder used, which underlines the importance of material selection in soil reinforcement.

The effectiveness of soil reinforcement in seismic areas has also been extensively studied. The impact of soil reinforcement techniques on foundation performance under dynamic loading conditions. Reinforced soils, especially those reinforced with fibers, show better resistance to liquefaction and seismic settlement. This has significant implications for earthquake-prone areas, where conventional foundations are prone to instability. The use of geocells and geogrids in seismic zones has been shown to improve the ductility and energy dissipation capacity of foundation systems (Krishna & Latha, 2022). In addition to structural stability, environmental sustainability is an emerging concern in soil reinforcement. Recent advances have focused on environmentally friendly reinforcement methods, such as biologically mediated soil improvement techniques. Microbially induced calcite precipitation (MICP) as a sustainable alternative to conventional cement stabilization. MICP significantly improves the shear strength of soil while reducing carbon emissions associated with traditional cement-based reinforcement. This method has shown promising results in reducing soil erosion and improving foundation durability in environmentally sensitive areas (Hang et al., 2021).

The long-term performance of reinforced soil foundations is another major consideration. Geosynthetic-reinforced soils maintain their load-bearing capacity over an extended period of time, with minimal degradation under cyclic loading conditions. The durability of polymer-based geogrids and geotextiles, which show that high-density polyethylene (HDPE) reinforcement exhibits superior tensile strength and resistance to environmental factors such as UV radiation and chemical exposure, strengthens the reliability of geosynthetic solutions for long-term infrastructure projects (Kim et al., 2025). Soil reinforcement plays a vital role in alleviating differential settlement problems, especially in expansive soils. Limestone columns effectively reduce tension and shrinkage in clay soils, thereby preventing foundation failure. The importance of proper reinforcement design is highlighted, highlighting those factors such as column spacing, depth, and type of binder significantly affect the effectiveness of soil stabilization techniques. The use of numerical modeling to predict settlement patterns has also been recommended to optimize reinforcement strategies (Fang et al., 2024).

Economic feasibility of soil reinforcement techniques is another important aspect of foundation engineering. Cost-benefit analysis conducted by comparing various reinforcement methods concluded that geosynthetic reinforcement is the most cost-effective solution for large-scale projects. Although deep mixing and chemical stabilization methods provide high early strength, they often incur higher material and labor costs. In contrast, geogrid and geotextile solutions offer a balance between performance and affordability, making them preferable for projects with limited budgets (Gowthaman et al., 2018). The integration of digital technology in soil reinforcement has revolutionized the design and monitoring of foundation systems. The application of machine learning in predicting soil behavior and optimizing reinforcement design. The use of real-time monitoring sensors embedded in reinforced soil structures further facilitates early detection of potential failures, allowing timely maintenance interventions (Sivasuriyan et al., 2023).

Case Study

The rehabilitation of a nine-story residential structure in Dakahlia, Egypt, that suffered severe tilting soon after construction is the subject of the research by Elsawwaf et al. (2023). Because of a significant misalignment between the raft's centroid and the structure's load center, as well as a thick, soft clay layer in the soil profile, the surface raft foundation-supported building experienced significant settling. The developers used a micropile underlying system to counteract the ongoing tilting. The paper describes the design techniques, micropile installation procedures, and geotechnical studies that were employed. The ideal quantity and location of micropiles were determined by evaluating three distinct design strategies. Even though the underpinning caused some settling at first, the micropiling successfully stopped more tilting. High-pressure grout injection was used in Type B micropiles, and load testing validated their advantages. In difficult soil conditions, the case study emphasizes how well micropile underpinning works to stabilize structures impacted by foundation settlement.

The authors Edens and Fisher (2018) presented three examples of micropile retrofitting. In the first project, twelve failed parking garage column piers in Lake Highland, Texas, were repaired using 36 micropiles; in the second project, a parking garage was constructed in the basement of a building that was over 50 years old in downtown Dallas, Texas; and in the third project, a coliseum was expanded using micropiles, structural bracing, and permanent soil nails. According to a case study published by Lopes et al. (2020), in 2010 two columns in a vacant section of the Federal University of Rio de Janeiro's hospital building fell, resulting in the destruction of the unoccupied portion and the subsequent settlement of the next block. Micropiles were first positioned beneath many pre-existing footings before jacked piles were adopted for the underpinning procedure. Thus, the findings shed light on the installation, settling, and arrangement of micropiles during drilling. A technique for correcting a slanted transmission tower supported on a shallow foundation in soft clay was presented by Wen et al. (2020). Hydraulic jacks supported by steel brackets fastened to the footing and grouted micropiles raised the tower. The grouted micropiles' bearing capacity was over 2.5 times more than that of the non-grouted steel pipe micropiles, it was discovered.

2. Conclusions

In foundation engineering, soil reinforcing is an essential method that enhances the stability, load-bearing capacity, and longevity of buildings constructed on unstable or weak soil. Numerous reinforcing techniques, including as deep mixing, micropiles, and geosynthetics, have been shown to be successful in reducing settlement and boosting soil strength. This study emphasizes how micropile underpinning is especially helpful in stabilizing buildings impacted by seismic activity and differential settlement, while geosynthetic-reinforced soil offers long-term stability with little deterioration. The examined case studies show how micropiles may be successfully used for foundation rehabilitation and retrofitting, especially in difficult soil situations. The necessity of choosing cost-effective solutions that are suited to the particulars of each project is further highlighted by the economic viability of various soil reinforcing systems. Additionally, the design, deployment, and upkeep of soil reinforcement systems have been improved by developments in digital technology, such as machine learning and real-time monitoring. All things considered, including suitable soil reinforcement techniques guarantees the lifetime and safety of infrastructure, making them essential to contemporary building methods.

This study admits a number of shortcomings that need more research. The diversity of soil characteristics is a major drawback that makes it difficult to create a universal reinforcing strategy appropriate for all geotechnical circumstances. Numerous site-specific elements affect the performance of reinforcing systems including geogrids, micropiles, and deep mixing, necessitating in-depth field research and practical testing. The long-term durability of geosynthetic materials and micropiles, particularly their resistance to aging effects, cyclic loading, and chemical exposure, should be the main focus of future study. The economic viability of alternative reinforcing techniques is another drawback since cost-benefit assessments varies for projects with varying budgets and soil types.

الملخص

تُعد تقوية التربة تقنية حاسمة في الهندسة الجيوتقنية لتحسين قوة التربة وثباتها وقدرتها على تحمل الأحمال لدعم أساسات المباني. يمكن أن تؤدي التربة الضعيفة أو الرخوة إلى فشل هيكلي وتسويات تفاضلية وعدم استقرار طويل الأمد، مما يستلزم استخدام طرق تقوية مختلفة مثل التكسية الأرضية والشبكات الجيولوجية ومسامير التربة وخلط التربة العميقة. يستكشف هذا البحث فعالية تقنيات تقوية التربة المختلفة في تعزيز أداء الأساسات وتحليل تأثيرها على قوة التربة وتقليل الترسبات والسلامة الإنشائية الكلية. من خلال الدراسات الميدانية والاختبارات المعملية، تقيّم الدراسة مدى ملاءمة طرق التقوية لأنواع التربة المختلفة وظروف التحميل. توفر النتائج رؤى قيمة حول تقنيات تثبيت التربة الفعالة من حيث التكلفة والمستدامة، وتقدم توصيات عملية للمهندسين والبنائين لتحسين تصميم الأساسات والبناء. يساهم هذا البحث في تطوير أساسات بناء مرنة ودائمة، مما يقلل من المخاطر المرتبطة بظروف التربة السيئة ويضمن السلامة الهيكلية على المدى الطويل.

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