# GROUND IMPROVEMENT TECHNIQUES FOR SUSTAINABLE ENGINEERING

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# Ground Improvement Techniques for Sustainable Engineering

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# Ground Improvement Techniques for Sustainable Engineering

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# PREFACE

In the evolving landscape of geotechnical engineering, the application of ground improvement techniques has become indispensable. Also, this domain has witnessed bountiful innovations in recent decades. With the increasing demand for construction using soil as an engineering material on less-than-ideal grounds, these techniques are essential, and they focus on enhancing the bearing capacity and reducing the settlement of weak soils, thereby ensuring the structural integrity and longevity of engineering projects resting over the soil. This book delves into the expansive subject of ground improvement techniques with special emphasis on techniques supporting Sustainable Development Goals (SDG). It offers a comprehensive exploration of methods designed to reinforce soft clays and loose sands, materials often deemed challenging due to their low bearing capacities and susceptibility to considerable settlement under stress.

This textbook presents readers with an extensive range of ground improvement methods, including compaction and stabilization, preloading and sand drains, lime-soil and stone columns, electro-osmosis, and grouting, as well as the use of geosynthetics and heavy tamping. Each approach is thoroughly examined, detailing its utility, efficacy, and scientific basis. The aim is to provide a wealth of knowledge for practitioners, scholars, and students that encompasses theoretical foundations, practical applications, and the most recent advancements in the field. This book delves into how these challenging conditions can be tackled through densification, dewatering, chemical stabilization, and other innovative techniques, thus transforming problematic soils into suitable foundations for construction. From conventional compaction methods to pioneering approaches involving geosynthetics, the content is designed to reflect the durable and cutting-edge strategies in ground improvement.

As we delve into the chapters, detailed discussions on techniques such as dynamic compaction, chemical stabilization, and stone-column installation provide insights into the complex processes and engineering principles involved. Additionally, modern challenges and solutions, such as the use of soil nails, micropiles, and ground anchors, demonstrate the adaptable and forward-thinking nature of geotechnical engineering. This book is an endorsement of the wide range of ground improvement techniques and serves as a guide towards their optimal and well-informed application in the pursuit of durable and resilient infrastructure development.

We are pleased to introduce this book, which is intended to serve as a helpful resource for individuals involved in the commendable pursuit of enhancing the land to promote human progress while preserving the Earth's well-being.

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## CHAPTER 1

# Enhancing Soil Density through Compaction

**Abstract:** Soil compaction is a key technique widely used in pavement and embankment construction. It is crucial to increase soil density and mechanical stability, enhance soil load-bearing capacity, and reduce the void ratio. This chapter delves into soil compaction, beginning with its basic premise as a mechanical method to enhance soil density by decreasing the air voids among soil particles, thus reinforcing the soil structure. The discourse differentiates between static and dynamic compaction, tailored for various soil types and project demands, where static compaction employs gradual pressure, and dynamic compaction involves vigorous impacts or vibrations. The efficacy of these methods is influenced by critical factors, such as soil moisture content and soil type (clay, silt, or sand), which dictate the compaction approach. The analysis extends to factors that impact compaction, highlighting the roles of soil texture, moisture, compaction energy, and equipment in achieving the desired compaction results. The discussion progresses to compaction control mechanisms, underscoring the need for real-time monitoring and adjustments to meet compaction goals while preventing soil overcompaction and damage. By providing an exhaustive understanding of soil compaction, this chapter aims to serve as an invaluable guide, shedding light on its practices, influences, and management strategies to optimize compaction in construction.

**Keywords:** Compaction, Dynamic compaction, Fill material, Highways.

## INTRODUCTION

The soil compaction improves the physical characteristics of the soil by reducing its permeability and compressibility and increasing its strength and load-bearing capacity [1]. Long before the fundamentals of soil mechanics were properly investigated, this fundamental knowledge of how soil responds to compaction was well known. In the past, those who built roads had an innate understanding that building roads with compacted soil produced higher-quality surfaces [2]. Soil compaction is still essential in modern civil engineering, particularly in the transportation industry. The Proctor curve, which first appeared in 1933 and supported scientific understanding of compaction processes, represented a significant advance in know-how and ability to optimize soil compaction [3]. Later, the California Bearing Ratio (CBR) test was introduced, which improved soil engineering even more and significantly contributed to the area. The fact that

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these inventions are still being used as industry standards speaks much about their continued usefulness and their robustness [4]. Soil behavior under loading in compacted and uncompacted conditions is an area of research undertaken by numerous researchers [3, 4].

Although analyzing the behavior of compacted soils under varying external and environmental stresses appears simple, it is a challenging task for engineers in the field. For example, the interaction with air conditions can majorly impact compacted soil and result in various behavioral patterns. Plastic deformation is demonstrated by swelling and collapsing once the soil is moist and splitting as the soil dries [5]. Moreover, soaking and drying cycles can cause changes in density in compacted soil [6, 7]. To ensure the endurance and strength of the infrastructure (see Fig. **1**), it is imperative to understand these intricate reactions to apply soil compaction techniques in civil engineering projects efficiently [8].

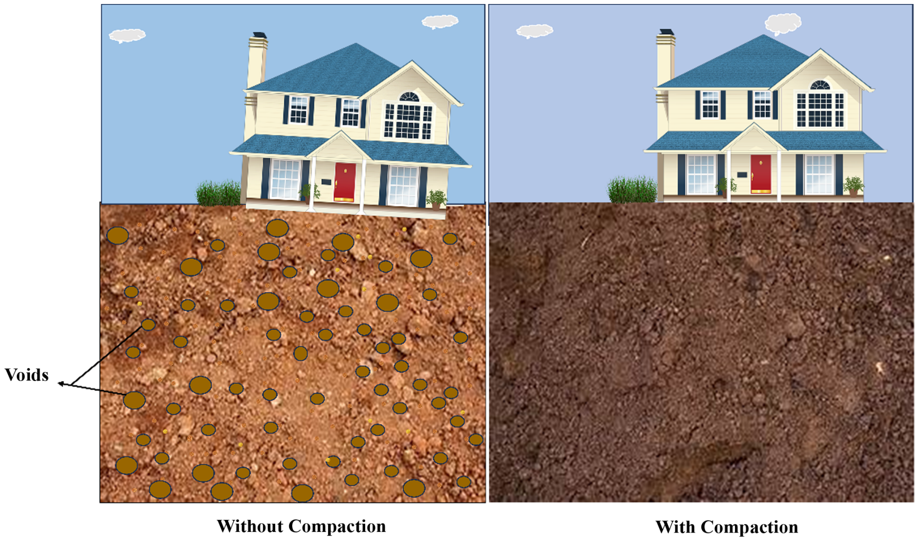

**Fig. (1).** Structure exposed with and without compaction.

Since the Roman era, soil compaction techniques have been essential for improving the ground in road construction. Higher-standard roads became necessary in the early 18th century as the interurban movement gained strategic importance [9]. France established the School for Bridges and Roads and the Engineering Corps to undertake research in this area [10]. Renowned 1765 alumnus Pierre-Marie Tresaguet revolutionized road pavement designs by including subbase layers, a technique he took cues from Roman engineering practices [11]. Similarly, Thomas Telford and John Metcalf used comparable design concepts in Britain. The use of huge stones for the pavement foundation posed a considerable obstacle to their designs, making construction time and expense prohibitive [11]. John McAdam addressed this problem by suggesting the use of smaller rock layers, which allowed for the creation of a denser layer that,*via*particle interlocking, offered support comparable to a massive stone foundation [12].

In early road construction, most soil compaction was done manually, with mechanized methods being rare. The need for durable road surfaces led to innovations in compaction machinery. In France, horse-drawn rollers were used for soil compaction, but the introduction of steam rollers in 1860 marked a significant improvement [13]. In the U.S., the sheep foot roller, inspired by the natural soil compaction from animals used in dam building in England, was developed in the 1820s. Early models applied substantial pressure but were relatively lightweight. With the advent of internal combustion engines in 1876, rollers could manage heavier loads, enhancing compaction efficiency [14]. Post-World War II, vibratory compaction technology became the standard, with vibrating rollers particularly effective for achieving high-density compaction in granular pavement layers [14]. This evolution highlights the shift from manual labor to advanced mechanical systems, improving road construction methods and infrastructure durability.

Over the last decade, numerous countries have significantly developed high-speed railways and metropolitan pavements, enhancing global transportation infrastructure [15]. This expansion has driven advances in design, construction, and maintenance technologies, focusing on strict safety and performance standards such as minimal subgrade settlement and reduced subgrade heave after construction.

To meet these challenges, innovative solutions have emerged, including the use of advanced subgrade fill materials and ground improvement techniques. For example, modern machinery for compacting subgrade soils, particularly vibratory rollers, has improved stability and efficiency. Current advancements in road compaction equipment include the development of automated, intelligent, and GPS-integrated vibratory rollers [16]. These intelligent machines feature adjustable modes and are at the forefront of road compaction technology. Additionally, the integration of the Internet of Things (IoT) and the management of compaction parameters allow for real-time analysis and optimization of compaction processes [16]. This chapter explores various types of compaction methods, their field applications, and the latest technological advancements, focusing on factors influencing compaction performance and outcomes.

## CHAPTER 2

# Engineered Soil through Stabilization: Sustainable Practices

**Abstract:** Engineered soil is a special type of soil in which the characteristics are altered through the addition of a stabilizing agent, a special type of material that alters the properties. This chapter offers an in-depth exploration of soil stabilization, a crucial technique in enhancing soil properties to meet construction requirements. Mechanical stabilization relies on physical modifications through compaction and soil blending against chemical stabilization, where admixtures are introduced to the soil to improve its characteristics. A detailed examination of various admixtures, including lime, cement, and industrial by-products, is provided in this chapter to give insights into their compatibility with different soil types and their effects on soil strength, durability, and permeability. Emphasis is given for a better understanding of soil conditions such as moisture content, type, and organic matter alongside the choice and proportion of admixture as pivotal factors determining the stabilization outcome. The enhancement of soil properties through chemical and mineral admixtures is highlighted, showcasing their role in augmenting soil strength, enhancing resistance to environmental stresses, and mitigating shrink-swell potential, collectively contributing to the longevity of construction undertakings. Furthermore, the chapter delves into field construction methods for soil stabilization.

**Keywords:** Cement, Cation exchange, Expansive clay, Pozzolanic material.

## INTRODUCTION

Soil stabilization is a technique of enhancing soil characters by blending and combining various admixtures, both chemical and minerals, targeting an increase in specific parameters. Measures to strengthen roadways and other geotechnical projects focus on raising the dry unit weight, load capacity, volume changes, and the efficiency of *in situ* subsoil, gravel, and other waste materials. In general, cement or lime is added to the soil to stabilize it since they are well-known binders [1]. These stabilization techniques enhance the soil's engineering qualities, producing a better construction material. The benefit of soil stabilization is an increase in soil strength and durability stiffness, as well as a decrease in soil plasticity and swelling/shrinking potential [1]. The stabilizing concept is very old, and successful techniques have been adopted for centuries. According to McDowell, lime was employed as a stabilizer by the Greeks and Romans, and stabilized earth paths were commonly used in ancient Egypt and Mesopotamia [2]. However, recently noted heaving and early pavement failures in sulfate-containing subgrades treated with lime and cement raised concerns about the efficacy of calcium-based stabilization [3]. When expansive soils with sulfates are treated with calcium-based stabilizers, the stabilizer's calcium combines with the sulfates and alumina to produce the expansive mineral ettringite. The first soil stabilization tests in the United States were conducted in 1904 [4]. As a stabilizer, cement was first used to build a street in Sarasota, Florida, in 1915 (ACI 1997), and lime was first used on short parts of the highway when roads were widened to accommodate the increase in vehicle traffic in 1924 [5]. To alter engineering characteristics and to stabilize soil, traditional stabilizers frequently rely on pozzolanic processes and cation exchange. Cementitious compounds are created when siliceous and aluminous particles interact with calcium hydroxide chemically at standard temperatures [6]. On the other hand, a cation exchange process also occurs when the soil exchanges any free cations that are present in the exchange areas.

Many studies have been carried out stabilizing expansive soils with additives such as lime, fly ash, or cement, with the aim of reducing their susceptibility to swelling and shrinking [7, 8]. This stabilization process involves introducing additives that contain calcium oxide, which initiates the flocculation of clay layers by exchanging monovalent ions with calcium ions ($Ca^{2+}$) [9]. As a result, clay particles aggregate to form flocs, which neutralize the electrostatic charges of the clay layers and reduce the electrochemical forces of repulsion between them. This causes the soil's engineering characteristics to change, making it more granular in structure, less flexible, more porous, and, most significantly, less expansive. Additionally, pozzolanic processes are promoted by raising the pH to about 12.4 by the interaction of hydroxide ions ($OH^-$) with the soil. The clay's silicon (Si) and aluminum (Al) components dissolve and interact with the calcium ions present during these reactions to generate cementitious materials such as calcium silicate hydroxides (CSH) and calcium aluminate hydroxides (CAH) [10]. These compounds significantly improve the mechanical properties of the soil while decreasing its plasticity nature due to their cementing effect.

The strength of stabilized soil over time is influenced by several key factors. The type of binder used plays a significant role, though its effectiveness can vary based on the specific soil type. Other factors that impact strength development include the binder quantity, the intensity of mixing, the curing temperature, and the stress applied during the curing process. The binder must be chosen to meet both short-term and long-term strength requirements for both drained and undrained conditions. Durability is essential, particularly when the soil is subject to aggressive groundwater or variable conditions. Rather than identifying an optimal binder for every case, it is more practical to consider the general strength levels and the rate of strength increase associated with different binders. The application of an initial load shortly after mixing, especially in peat stabilization, can significantly improve the soil's strength. Preloading helps to form a more consistent stabilized mass and provides a stable surface for continued work. While preloading in the field results in slower consolidation compared to laboratory tests due to longer drainage paths, the curing process eventually strengthens the soil, reducing further compression. Ultimately, the strength of stabilized soil is affected by both the stress and drainage conditions it experiences. Tests such as unconfined compression tests are valuable for assessing the strength levels achieved and for comparing the performance of various binder combinations.

This chapter highlights the improvements in expansive soil properties after adding different additives, emphasizing the two goals of stabilization initiatives: reducing the soil's tendency to shift in volume and strengthening its mechanical properties, which are important for civil engineering uses.

## MECHANICAL STABILIZATION

Mechanical approaches have been utilized in engineering practice for the treatment of expansive soils over the years. These approaches aim to reduce swelling stress and expansion potential without altering the chemical makeup of the soil. To achieve this, cohesionless soil is mixed with expansive clay to minimize swelling and shrinkage. In general, the fine sand content and fines content in the expansive soil were arbitrarily varied between 425 and 300 µm and 150 and 75 µm, respectively, based on the grain size. It was found that the swell potential and swelling pressure decreased with an increase in fine sand content, but they increased with an increase in fines content. The coefficient of compressibility, coefficient of volume compressibility, and compression index of the samples decreased initially up to a sand content of 15% and then increased at higher sand contents. This decrease is attributed to the improved particle interlocking and reduced compressibility of the soil-sand mixture, as the sand particles fill voids and enhance the overall stability of the matrix. The excess sand disrupts the soil structure, reduces the cohesive properties, and creates a looser matrix, thus increasing compressibility at higher sand contents. However, one of the drawbacks of clay-sand and clay-gravel mixes is that they allow for faster water ingress due to increased permeability.

### Methods of Mechanical Stabilization

To obtain good quality engineered soil that can meet these three essential criteria, the soil must first be compacted so that (i) reduction of the soil's ensuing settling under live loads, (i) reducing permeability earth dams are protected from concerns

## CHAPTER 3

# Enhancing Ground Support: Lime-Soil and Cement-Soil Columns

**Abstract:** In this chapter, the evolution and application of ground enhancements through lime-soil and cement-soil columns are explored, emphasizing their interaction with native soils, formation mechanisms, installation techniques, load behavior, and effectiveness in soft soil environments. It also presents an in-depth investigation into the chemical dynamics between soil particles and the binder's lime and cement, revealing how these interactions significantly improve soil strength, elasticity, and longevity. The chapter further dissects the processes of forming these soil columns, presenting a detailed guide on achieving a cohesive and robust load-bearing structure. Installation methodologies are critically analyzed, focusing on disseminating the importance of choosing appropriate methods to attain the desired outcomes in ground support. Additionally, the performance of lime-soil and cement-soil columns under varying loads is scrutinized to demonstrate their capacity to enhance load distribution and bearing capabilities. Special attention is given to their application in soft soil areas, highlighting their role in overcoming settlement challenges and boosting infrastructure stability. Key factors affecting the behavior and efficacy of these columns, such as binder concentration, soil typology, curing duration, and environmental conditions, are thoroughly discussed. This chapter contributes significant insights and empirical evidence to the civil engineering domain, advocating for the expanded use of lime-soil and cement-soil columns to tackle soft soil challenges and promote environmentally sustainable construction methodologies.

**Keywords:** Cation exchange, Embankment construction, Lime column, Soft clays.

## INTRODUCTION

Lime and lime cement columns are normally 0.5 to 0.6 m in diameter and are made up of stabilized clay prepared using lime or lime-cement mixture [1]. Using a lime column mixer, burnt lime that has been finely ground is combined with soft clay to stabilize lime. Ordinary Portland cement is mixed with lime in lime/cement columns. In lime/cement columns, the percentages of lime/cement by weight are typically 50/50 [2]. Clays that respond favorably to mixing go from soft clay to solid clay that resembles a dry crust. Outside of the stabilized zone, the soft clay is primarily unaffected. Columns made of lime and lime/cement

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possess significantly higher shear strength and compression modulus than those made of unstabilized clay [3]. These columns, once placed, will increase the bearing capacity of soft clay, and the enhancement of strength depends on the distance between the columns. Consolidation settlements beneath a loaded surface will be lower than for unstabilized clay due to the columns' higher compression modulus [4]. The other method involves using very tiny but specialized equipment to inject lime slurry under pressure into a sloping area. This process is known as a lime-pressurized slurry injection [5]. The United States of America employed this technique of slurry injection to stabilize slopes [5]. Another technique is the lime column/pile technique, which involves drilling holes in soft soil deposits, filling them with quick lime, and compacting the mixture. Much research has been done in the UK on the lime heaps approach [6, 7]. A successful stabilization method for unstable sub-grade and foundation soil is lime columns or piles. In addition, it can be applied as a slope stabilization method for sea walls, breakwaters, highway barriers, water-preserving structures, and excavation structures requiring bracing [8].

The columns' clay mixture, which also contains lime and cement, is not uniform. Stabilized clay is produced into lumps when combined with cement and lime. The joints between the lumps have a lower shear strength than the lumps themselves. The mixing method also causes the columns to create layers roughly at right angles to their longitudinal axis [9]. Due to the uneven structure of lime/cement columns, they have a far higher permeability than unstabilized clay, which results in the following outcomes: (i) the shear strength changes inside the column in various directions, and ii) the consolidation settling is accelerated by the column, which functions as a vertical dram. Lime has minimal to no stabilizing impact on organic soils with high organic content (> 6%) and higher water content (> 120%) [10]. This indicates that lime or lime/cement columns should not be used in organic soils like peat, and they are seldom recommended.

The stabilized soil that was made using a lime column or pile had a significantly higher stiffness than a lime-cement column [11]. After working on several case studies and theoretical investigations, many researchers concluded that lime piles and columns strengthen and stifle *in situ* soils. The shear strength increase that occurs with lime columns is greater than the predicted theoretical value [12, 13]. Compacted soil columns with lime will boost the surrounding soil's load-carrying capacity and also decrease settlement [14]. Additionally, it was determined that for column diameters larger than 100 mm, the changes in stiffness became insignificant, meaning that the results can be extrapolated to anticipate the behavior of full-size columns [14]. Comparing the shallow mixing and column performances of lime, gypsum, and fly ash in swelling soils, found that lime caused the largest decreases [15]. Numerous researchers have conducted numerical experiments utilizing different finite element-based software packages to understand the effect of utilizing stone columns as a stabilizing agent [16, 17].

## MECHANISM OF TREATED COLUMN

Burnt lime is slaked when it interacts with the water in the clay. Heat is produced as a result of the reaction. Slaking is a rapid procedure that is completed within one hour of lime mixing. Following the slaking of the lime, ion exchange occurs, in which the dissociated univalent calcium, sodium, and ammonium ions swap places with the dissociated divalent calcium ions. Each calcium ion can bind two clay particles, which causes the clay's structure to become more granular. The addition of lime triggers the clay's ion exchange and structural alteration. Thus, the strength begins to increase immediately, albeit it can take many months for the ion exchange to be finished. The strength increases quickly and then slows down until the process is complete. The remaining lime from the second stage reacts with the silicates and aluminates the clay in the third step. Strong binding and low solubility compounds are generated. These serve as a glue between the clay granules, strengthening the lime column. For several years, the lime and clay mixture has been hydraulically stabilized. The pH in the columns must be at least 8 after mixing in the lime for these chemical processes to occur [18]. The chemical process could be delayed or even stopped by a low ground temperature at the ground's surface.

When added, the cement reacts with the mixture's water, increasing the combination's strength. Compared to cement, stabilization with lime often provides considerably less strength during the first several months. However, in soil stabilized with simply lime, the shear strength increases significantly over time.

To strengthen and lessen the compressibility of the weak soil, deep soil mixing involves blending the unstable soil with cementitious materials and additional additives to create a soil binder column. This technique mainly relies on adding a strengthening additive, such as cement, lime, gypsum, or fly ash, to the natural soil to increase its stiffness. Worldwide, deep soil mixing techniques and built foundations have been used to support excavations, embankments, and structures [19]. The qualities of the local soil, the blending technique, and the binder properties could all be reflected in the attributes of the upgraded soil column [20]. Depending on the native soil's moisture level, deep soil mixing techniques are divided into wet and dry categories. The wet deep mixing approach creates a soil-binder column by injecting cementitious slurry *via* a large diameter to a predetermined improvement depth. In the case of the dry deep mixing method, the typical procedure involves rotating a mixing tool into the native soil to break up

## CHAPTER 4

# Preloading Techniques and the Role of Vertical Drains

**Abstract:** This chapter delves into the productive application of preloading techniques and vertical drains, predominantly known as Prefabricated Vertical Drains (PVDs), in ground engineering to enhance the properties of soft soils. A comprehensive overview of various vertical drain systems is provided in this chapter, elucidating their respective advantages and applications in soil improvement projects. Particular emphasis is placed on PVDs, a contemporary practice heralded for its effectiveness in expediting the consolidation process of soft grounds. By facilitating a shorter pathway for pore water expulsion, PVDs significantly augment the strength and stiffness of soft soils over time. Through a detailed exploration of the mechanics behind PVDs, including installation practices, design considerations, and performance evaluation, this chapter aims to thoroughly explain these systems. It highlights the transformative impact of PVDs on soft soil stabilization, underpinning their role in optimizing ground engineering projects for enhanced durability and resilience.

**Keywords:** Consolidation, Marine clays, Reclamation worksPVD., Smear effect.

## INTRODUCTION

Soft soils are frequently found everywhere worldwide along deltaic and coastal areas. They are highly compressible and have undesirable geotechnical attributes like low permeability, low undrained shear strength, and high natural moisture levels almost at the liquid limit. Other examples of soft soils are peats, marshy soils, soft estuaries, and marine clays. Therefore, measures must be taken to enhance these soils so structures built on them can experience stability and serviceability issues. While pile foundations can be used to solve these issues in some circumstances, they might be excessively costly, mainly when supporting low-to-medium-rise buildings and dams [1]. In these situations, the earth must be adequate to support the load being placed by improving the soil within the structure's load transfer zone [2]. Enhancing the ground basically entails bringing the soil's shear strength and compressibility to the appropriate level. Around the world, several soft ground engineering techniques have been employed, including deep soil mixing, vacuum consolidation, stone columns, preloading alone, and preloading with vertical drains [3 - 5].

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Preloading and vertical drainage are two ground improvement techniques frequently used in civil engineering projects to prepare the ground for large constructions like buildings, highways, and airports, with a prime focus on consolidating and strengthening loose soil [6]. Preloading adds to the soil's surface load by imitating the weight of the anticipated construction, commonly with sandbags or temporary structures. This procedure increases the soil's bearing capacity and decreases future settling by forcing water out of the pore spaces and hastening the consolidation of the soil [7]. The purpose of vertical drains, which are frequently combined with preloading, is to quicken the consolidation process. These drains are placed vertically through the fragile soil layer and down to a more stable layer. They are usually constructed of prefabricated materials such as wick drains or sand columns [8]. Compared to natural settlements, they significantly shorten the time needed for consolidation by acting as conduits for water to escape vertically. Preloading and vertical drains work well together to stabilize the soft ground, guarantee a strong and dependable foundation for building projects, and reduce long-term settlement problems [9]. The hydraulic conductivity of the majority of sedimentary deposits is anisotropic, with the horizontal portion being at least twice as large as the vertical portion. As a result, the consolidation coefficient for horizontal pore water flow is greater than the consolidation coefficient for vertical flow [10]. These two effects mean that, in contrast to years in preloading, the time required to attain the necessary degree of consolidation is reduced to a few months [11].

## PRELOADING

Preloading enhances soil characteristics by applying a surcharge load to the ground. This method is particularly useful for compressible soils and areas with a shallow water table. A uniformly distributed load is applied to the surface before the actual construction begins. Depending on the project's needs, part or all the surcharges may be removed before construction starts. The temporary overload remains in place for a specified duration, after which the structure can be constructed with minimal or no further settlement.

### Conventional Preloading

Before construction and the placement of the final construction load, preloading often refers to the process of compressing the soil under imposed vertical stress. The two most widely used preloading methods are vacuum-induced preloading and conventional preloading, such as preloading using an embankment.

Preloading is the simplest preloading solution, such as using an embankment. The pore water initially carries the load before it is placed on the soft soil. The water pressure will progressively diminish when the soil is not particularly permeable, which is typically the case because the pore water can only move away very slowly in a vertical direction. The load must often be applied in two or more phases to avoid stability issues; Fig. (**1**) depicts this principle. Surcharge load is used to describe the surplus if the temporary load is more than the final construction load. When settlements exceed the anticipated ultimate settlement, the temporary surcharge may be eliminated. Preferably, this occurs once the remaining extra pore pressure becomes lower than the stress increase brought on by the transient surcharge. Secondary settlement can be slowed down or even prevented by lengthening the temporary overloading period or increasing the overload's magnitude. This is so that the soil will constantly be over-consolidated, and secondary compression for over-consolidated soil is substantially smaller than that of regularly consolidated soil. This is accomplished by applying a surcharge larger than the workload.

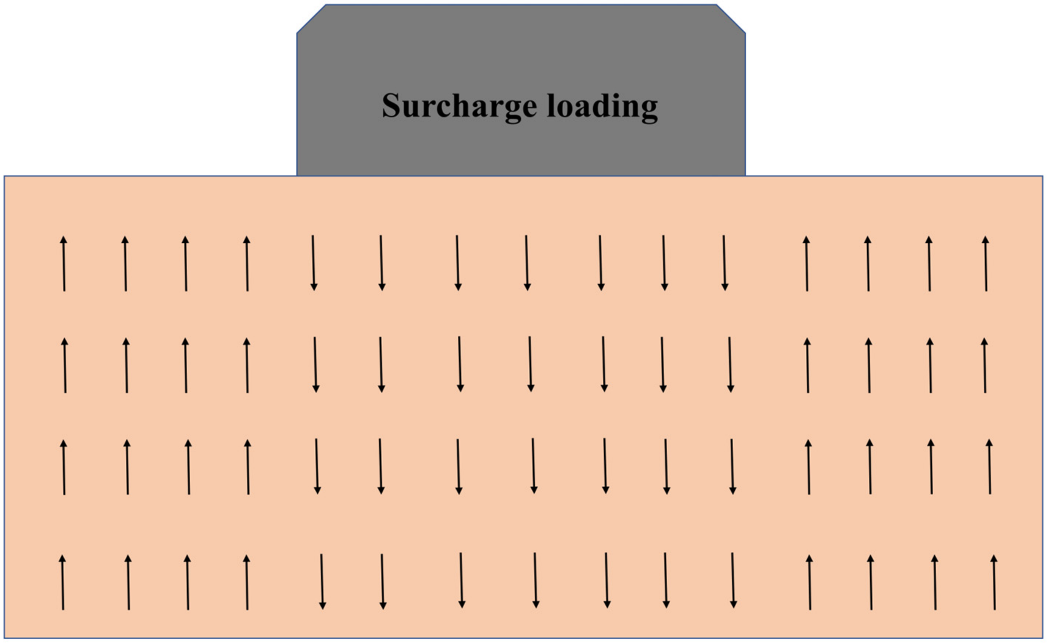

**Fig. (1).** Preloading mechanism.

## Vacuum Preloading

A fill embankment may only sometimes be possible since the soft soil may occasionally be so unstable that even a standard 1.5 m embankment may already provide stability issues. Using the vacuum preloading approach may be appropriate. Kjellman was the first to adopt vacuum preloading in 1952 to quicken consolidation [12].

## CHAPTER 5

# Reinforcing Soft Grounds: The Utility of Stone Columns

**Abstract:** This chapter conveys the utilization of stone columns, a proven method for enhancing the engineering characteristics of soft clayey grounds and loose silt deposits. By facilitating accelerated consolidation through reduced drainage paths and bolstering the load-carrying capacity while curbing settlements by integrating robust, granular materials, stone columns significantly improve soil stability. The discussion encompasses the techniques and construction methodologies of stone columns, elucidating the underlying mechanisms of their behavior under load. It further explores the design principles that guide their application and integrates insights from contemporary research findings, offering a comprehensive overview of stone column utility in reinforcing soft grounds.

**Keywords:** Consolidation, Failure mechanism, Flexible foundation, Soft clays.

## INTRODUCTION

Due to rapid development both in industries and the residential sector, there is a need for more land with outstanding geotechnical characteristics. Most engineers are considering *in situ* improvement of poor soil deposits due to the rising property value and scarcity of suitable construction locations [1]. Several methods for ground enhancement have been developed to establish marginal locations profitably. One technique for improving the ground with a track record of success is using stone columns [2]. Moreover, the idea was originally used to improve local soil in France in 1830 [3]. In numerous challenging foundation sites across the globe, stone columns have been employed to boost bearing capacity, decrease overall and differential settlements, accelerate consolidation, enhance slope stability of dams, and enhance liquefaction resistance [4 - 6]. When building a stone column, unsuitable underlying soils are partially replaced by a compacted vertical stone column that typically penetrates the weak layers fully [7].

Compared to native soil alone, the composite material produced by the more robust column has a higher shear strength and a lower total compressibility. Except for pile caps, structural links, and extensive penetration into underlying hard strata, stone column systems in soft, compressible soils are like pile

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foundations; the main difference is that the stone columns are considerably more compressible [8]. As opposed to transferring the pressures into a deeper layer, as in the case of a pile foundation, the stone columns distort when loaded by bulging into the subsoil layers and distributing the stresses at the upper area of the soil profile, enabling the soil to withstand it [8, 9]. Because stone columns tend to expand during shearing and drain the extra pore pressures generated, they reduce the chance that loose sand deposits would liquefy due to earthquakes [10, 11].

Stone columns can also serve as vertical drains, accelerating the area's consolidation of soft clay soils. Over the past thirty years, numerous studies have examined the effectiveness of earth stabilization using stone columns [11]. It has been shown that reducing the bulging of these columns can enhance their performance and reduce soil settlement. When stone columns are encased with geosynthetics, their bearing capacity can increase by three to five times compared to traditional stone columns, though the benefits of encasement diminish as the column diameter increases [11]. Additionally, placing a sandy layer over the stone columns helps distribute stresses evenly and provides drainage. When reinforced with geosynthetics, this sand layer significantly improves the bearing capacity. This chapter highlights the importance of stone columns, explores various construction methods, and discusses the latest advancements in this field.

## STONE COLUMN MECHANISM

Stone columns are often composed of materials that are more permeable and granular, which may contribute to the acceleration of consolidation settlements and the reduction of post-construction settlements (refer to Fig. **1**). Additionally, the installation of stone columns can positively impact the *in situ* stress conditions.

Stone columns are commonly employed to support structures on loose silty sands with more than 15% fine particles and in very soft to firm cohesive soils, enhancing load-bearing capacity and soil stability [12]. Stone columns are used to support low-rise buildings such as raft foundations, liquid storage tanks, and embankments [13]. Ideal soils for stone columns have undrained shear strengths between 7 and 50 kPa. Vibrated stone columns can now be employed as a viable alternative to conventional treatment techniques, including pilings for low-rise buildings.

The enhancement in ground-bearing capacity is attributed to the reinforcing effect provided by the stone columns, as they facilitate faster sub-soil consolidation through vertical drainage. Being significantly stiffer than the surrounding soil, the stone columns absorb and transfer a substantial portion of the applied vertical load, leading to an overall improvement in ground stability (Fig. **2**) [14].

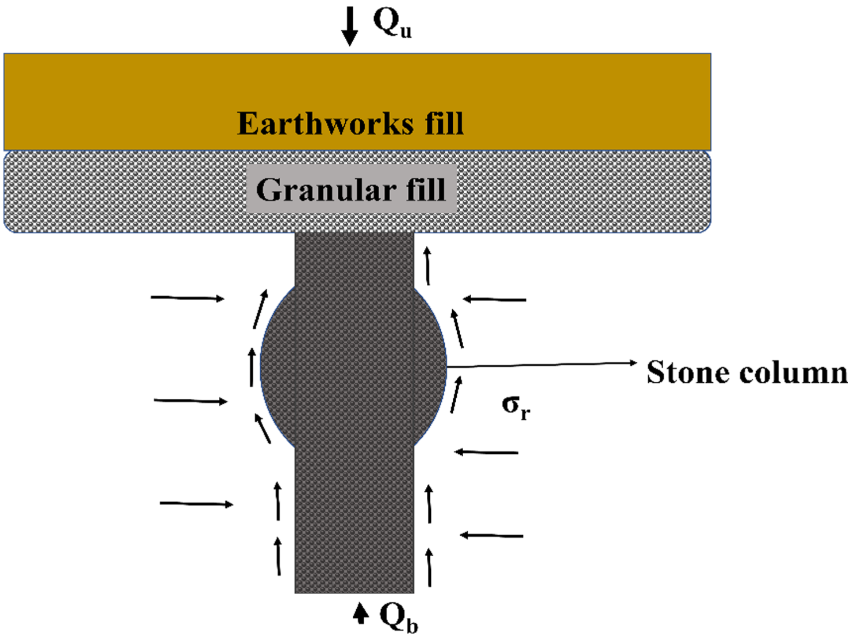

**Fig. (1).** Stone column working mechanism.

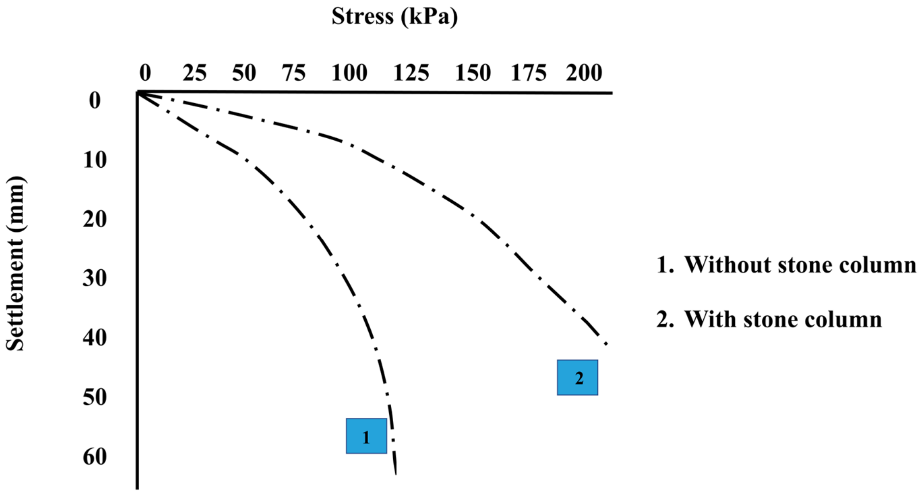

**Fig. (2).** Stone column effectiveness.

## STONE COLUMN CONSTRUCTION

Stone columns are formed by making boreholes in soft soils and filling boreholes with stones that are compacted. When a structure is placed over the area treated by stone columns, the majority of the load is transmitted to stone columns because

## CHAPTER 6

# Strengthening Substrates: Grouting Methods

**Abstract:** This chapter looks into the crucial role of grouting as a soil improvement technique aimed at enhancing construction foundation stability, facilitating open-cut excavations, and supporting tunneling operations. By focusing on the dual objectives of reducing soil permeability and augmenting its strength, the discussion mainly revolves around the traditional use of cement and lime treatments alongside the application of chemical grouts for finer geological textures. Through a critical examination of critically examining various research studies, the aim of this chapter aims to provide practicing engineers with a comprehensive overview of grouting methods, tracing their evolution from historical roots to contemporary practices. It elaborately discusses the spectrum of grouting materials, injection methodologies, pertinent equipment, and the inherent limitations and verification protocols associated with each type of grout. Highlighting the dichotomy between suspension-based permeation grouting and chemical solutions, the narrative underscores the efficiency of suspensions in coarser soils and the suitability of chemical solutions for finer strata. Moreover, it addresses certain chemical solutions' environmental and health concerns, noting the shift toward environmentally benign inorganic suspensions. Ultimately, the chapter serves as a resourceful guide for contractors and consultants, offering valuable insights into designing and implementing grout fluid injection works, thus promoting best practices in soil improvement and substrate strengthening.

**Keywords:** Chemical grouts, Rock fissures, Tunneling, Weak soil.

## INTRODUCTION

Historically, Belic used lime and clay grouts to support the strata when he first proposed grouting in 1802 [1]. At the moment, the two main ingredients in grouts are still lime and clay, with lime-based grouts being widely used for the grouting of shield tunnels in stable strata [2]. Cement was invented in 1824, but it was not until England used it for grouting in 1850–1860 [3, 4]. Cement is currently the most widely used cementitious material in grouts, and numerous types of cement-based grouts have been developed for shield tunnel applications [5, 6]. Currently, shield tunnel grouting in soft soil strata is done primarily with cement-based grouts. British engineers created chemical grouts in India before the 19th century [7]. Germany and Belgium subsequently acquired patents for cement, sodium silicate, and double-liquid grouting during the early 19th century [8].

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There are several uses for soil grouting, and it is applied in many fields. The most commonly used applications are *in situ* reinforcement, stabilizing and densifying deep foundations, barrier systems to limit water flow, and corrective measures for post-construction issues in soft or loose deposits [9]. To improve the physical and mechanical qualities of deep foundation soils, a stabilizer is injected during the stabilization process, known as soil grouting. Stabilizers, which help to densify and waterproof the soil deposit, are typically combinations of chemicals or soil additives. As a result of this newer domain, technical standards were created to create a consistent approach to materials, procedures, and techniques. However, several criteria lack specificity in their composition and do not restrict the application of a certain attribute [10, 11]. Gullu *et al.* [12] found that it is difficult to even define the term 'grout'. The most acceptable is that "grout" refers to a variety of injectable fluid materials that may be manipulated and constructed in numerous ways to obtain the desired outcome [13], but this is more of a characteristic than a definition. Hence, a cementitious grout is defined as a fluid mixture injected into the soil for a variety of purposes, including filling voids and cracks, bonding pre-cast concrete elements, stabilizing soils, sealing joints, and filling ducts of post-tensioning tendons in prestressed elements [14]. The fluid mixture comprises cement, fine aggregates, water, and chemical admixtures. It is obvious that the characteristics and composition of the grouts vary depending on the application. For example, because there may be a movement of water in the rock, low-viscosity grouts are usually not recommended for lifting constructions. Grouts with a quick setting time are best suited for this purpose [15]. The grooves used to fill the post-tensioning conduits must be very stable and fluid in order to cover the maximum amount of the ducts; otherwise, losses may result from structural movement. Sedimentation and bleeding can also be seen in unstable grouts. Depending on the weather, free water can freeze or evaporate, which could cause expansion and/or corrosion problems [16]. The joints in pre-cast concrete are crucial and the grout that is used should have the least shrinkage and good binding strength [17]. The literature on potential grouting applications offers a wide range of possibilities. This study should include, among other things, grouts used for soil nailing [18], steel reinforcement [19], structural repair [20], soil erosion treatments [21], masonry [22], pavement [23], and tunneling [24]. Fluidity is always a crucial component of the characteristics of the grout. Although a high fluidity may cause an equally high bleeding rate, which would impair the application's performance, a low fluidity is necessary to fully and efficiently fill all vacant areas in the designated grouting domain. An overabundance of free water may potentially cause issues with corrosion and/or expansion in reinforcement. Numerous studies have examined the effects of adding chemical admixtures [25, 26] and supplementary cementitious materials [27 - 29] in addition to controlling fluidity, with the goal of improving permeability, durability, and strength. The grouting industry also made an effort to address concerns about the detrimental effects of the construction industry by introducing innovations, ranging from novel grout formulations for well-known uses to eco-friendly compositions [30, 31].

## GROUT MATERIALS

Grout is a viscous (solid, sticky liquid that never flows easily) packable material that is used to fill the gap between two parts to bind them together or create a water-resistant seal. To cover the gaps, grout is typically made of cement and water. Additionally, it gives the foundations of load-bearing structures more strength. The engineer must understand the many types of grout and their qualities to create grouting work for specific conditions. Below is a discussion about the categories of grouts that are now in use, along with their characteristics. The different kinds of admixtures and fillers used and how they affect the grout are also covered. Cement, clay, chemical, and asphaltic grouts are typical grouts used for this purpose. Each grout has characteristics that make it attractive in specific situations. The grout must have particles significantly smaller than the spaces to be filled, which is a crucial criterion. According to the composition, three basic types of grout are differentiated as given below.

### Suspension Grouts

These are the grouts in which small solid particles are distributed in a liquid dispersion medium. Common suspension grouts are cement and clay grouts.

Cement grout consists of a mixture of cement and water. It effectively stabilizes rocks with fissures, gravel, and coarse sands. The ratios of water cement may vary from 0.5:1 to 5:1 depending on the conditions of the terrain and the required strength [32]. Lower water-cement ratios involve less segregation and filtration but require higher injection pressures and lead to more friction losses in the pumping system. The setting time for cement grouts is approximately 4 –24 hours, depending on the added additive [33]. The stability of cement grout can be increased by adding bentonite (to control bleeding). Microfine cement has become an alternative to more toxic chemical grouts and is used for improving underground strength in combination with sodium silicate for underground water control. Cement is not classified as a chemical grout but as a suspension grout. The strength of cement grout in sands and gravels after complete setting is about 1 MPa.

To prevent micro cracks forming, cementitious grouts must fill spaces and joints, adhere well to surfaces, resist chemicals and mechanical stresses, and shrink as little as possible. Depending on application or formulation, cementitious grouts

## CHAPTER 7

# Geosynthetics: Revolutionizing Ground Improvement

**Abstract:** This chapter examines the transformative impact of geosynthetics on ground improvement, spotlighting their role in fostering sustainable solutions for various geotechnical and geoenvironmental challenges. By synergizing with traditional and unconventional construction materials, geosynthetics amplify their environmental benefits, aligning with global movements towards sustainable development and a circular economy. The discourse explores various geosynthetic applications, from reinforcing soil structures and enhancing landfill drainage systems to creating practical barriers and stabilizing embankments over soft grounds. Special attention is given to integrating natural materials such as coir and jute, underscoring their potential to further the environmental advantages of geosynthetics. This overview emphasizes the significance of geosynthetics in soil improvement practices, demonstrating their crucial contribution to eco-friendly engineering and the pursuit of global sustainability goals.

**Keywords:** Circular economy, Geo-environmental applications, Geosynthetics, Natural materials.

## INTRODUCTION

To ensure the long-term preservation of the environment and its resources, it is vital to address geotechnical and geoenvironmental issues. Geosynthetics offer environmentally friendly, sustainable solutions that use fewer natural resources and have a minimal impact on the ecosystem. These polymeric materials are specifically designed for geotechnical and geoenvironmental applications [1, 2]. According to ASTM D 4439, geosynthetics are defined as planar products manufactured from polymeric materials used with soil, rock, earth, or other geotechnical engineering-related materials as an integral part of a human-made project, structure, or system [2].

Geosynthetics are extensively used in various applications, including geotechnical, environmental, and hydraulic projects related to groundwater quality and management [3 - 5]. For instance, geotextile filters are commonly used in trench drains. Additionally, geosynthetics are utilized in base and cover liner systems for modern landfills to minimize the risk of groundwater contami-

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nation [5]. Furthermore, geosynthetics are increasingly being used in groundwater control applications. In groundwater cleanup and control projects, high-density polyethylene (HDPE) vertical barrier systems can be employed instead of conventional soil-bentonite cutoff walls [6]. As a result, the geosynthetics market is robust and rapidly expanding due to the continuous use of geosynthetics in established applications and the emergence of new uses for these products [7].

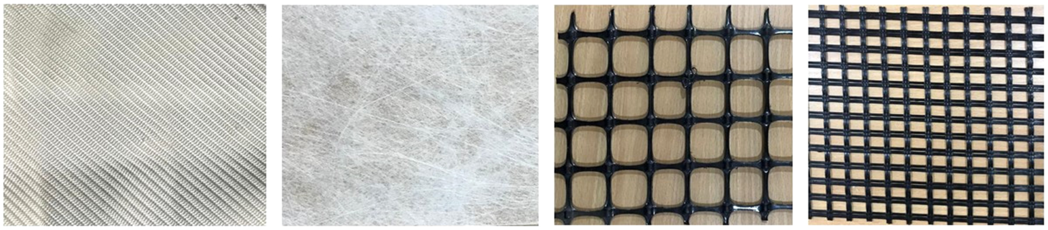
Geosynthetics has a wide range of applications that cater to the needs of engineers in designing geotechnical, environmental, and hydraulic systems. For instance, geotextiles can be used as filtration components in dams and waste containment systems, while geocomposites can function as erosion control elements in channels and slopes. Additionally, geogrids can reinforce soil embankments, and geotextiles can serve as filters in trench drains, geomembranes in landfill liner systems, and HDPE vertical panels in groundwater control projects [8, 9].

Numerous experiments have been conducted to understand the hydraulic and mechanical properties of geosynthetics, which are essential for both production and design [10, 11]. Engineering and index properties are used to describe the material characteristics that are vital for geosynthetic production and quality control. Some index properties may also be used for design if they are associated with relevant performance properties. It is essential to create geosynthetic products that meet the minimum requirements necessary to perform their designated functions effectively in a particular design [12]. Geosynthetics can serve various purposes, such as filtration, drainage, barrier, and protection.

Geosynthetics are typically manufactured in sheet form in a regulated environment and are delivered to the job site in rolls, which can be cut, folded, stacked, and packaged in cartons. At the project site, the geosynthetic sheets are unrolled and overlapped to create a continuous geosynthetic blanket, which is often physically attached using techniques such as welding for geomembranes or stitching for geotextiles. There are several types of geosynthetics, including geotextiles, geomembranes, geogrids, geosynthetic clay liners (GCLs), geocomposite sheet drains, geocomposite strip (wick) drains, geocells, erosion control products, and HDPE vertical barrier systems. Geosynthetics are commonly integrated into geotechnical, environmental, and hydraulic systems for a variety of purposes. For instance, they are used in the bottom and cover liner systems of waste containment facilities as an infiltration barrier, filtration, separation, drainage, protection, and reinforcement system [13].

## TYPES OF GEOSYNTHETICS

Preserving the environment and its resources is of utmost importance for both present and future generations. In this context, geosynthetics play a crucial role in proposing sustainable engineering methods to tackle geotechnical and environmental challenges. By incorporating geosynthetics into projects, there is a noticeable reduction in the use of natural resources, which helps to reduce environmental impacts. Geosynthetics come in various forms, each designed to perform specific functions in engineering projects, highlighting their versatility and significance in creating environmentally friendly and effective infrastructure solutions. Fig. (**1**) shows the various geosynthetics.



**Geotextile (Woven)** **Geotextile (Non-woven)** **Geogrid (Bonded)** **Geogrid (Woven)**

**Geomembrane** **Geocell** **Geonet** **Geocomposite**

**Fig. (1).** Types of geosynthetics.

Geosynthetics are manufactured from such as HDPE, Linear low-density polyethylene (LLDPE), Polypropylene (PP), Polyvinyl chloride (PVC), Polyester (PET), Expanded polystyrene (EPS) and Chlorosulphonated polyethylene (CSPE) (see Fig. **2**). In synthetic polymers, high-density polyethylene, polyester, and polypropylene are some of the most widely used materials. Introduced in 1954, polypropylene is a semi-crystalline thermoplastic material with a density ranging from 0.9 to 0.91 g/cm$^3$ [14]. Although stabilizers and additives must be used to improve the material's resistance during manufacture, its affordability and versatility for different molding methods make it a popular option. On the other hand, polyester is a thermoplastic with a density that falls between 1.22 and 1.38 g/cm$^3$ [15]. Its remarkable chemical tolerance distinguishes it, its only weakness being extremely high pH conditions. The melting points of polyester and polypropylene are different; PET melts at about 260 °C, while PP melts at about 165 °C [16]. Geomembranes are commonly made of polyethylene, which is

## CHAPTER 8

# Soil Nailing for Enhancing Slope Stability

**Abstract:** This chapter explores the soil nailing technique, which is an innovative approach used for stabilizing slopes, embankments, tunnels, and retaining walls, and presents it as a versatile, cost-effective, and environmentally friendly solution among the various geotechnical stabilization measures. It provides a detailed examination of the favorable ground conditions for soil nailing, detailing its advantages and limitations compared to traditional stabilization methods. The narrative meticulously describes the installation processes crucial for the success of the technique and highlights potential failure modes to equip practitioners with the foresight required to mitigate risks. Emphasizing the response to soil nails pullout as a critical design parameter, the chapter evaluates the effects of grouting pressure, overburden pressure, soil dilation, degree of saturation, nail surface roughness, and borehole conditions on the pullout capacity through a comprehensive review of the literature. By scrutinizing construction parameters and their impact on design methodologies, the chapter advocates an organized and informed approach to soil nailing, emphasizing the importance of a multifaceted consideration of variables to achieve optimal slope stability.

**Keywords:** Embankment slope, Grouting, Landslides, Retaining support.

## INTRODUCTION

By inserting relatively thin sections of typically steel reinforcing bars, soil nailing is used to reinforce naturally occurring or artificially created soil slopes, excavations, or retaining walls. Building a retaining wall for highways, slope support, excavation support, and bridge abutments is a cost-effective and efficient method [1]. Shale, cohesive soil, broken rock, and fixed face conditions suit this technique. In the middle of the 1970s, soil nailing was first noted to have been used in the United States [2]. The idea of soil nailing originated in Europe as a means of restoring old retaining walls, repairing earth barriers that had fallen into disrepair too soon, and stabilizing natural slopes both temporarily and permanently. In France, the first application was lodged in 1972 [3]. In addition, soil nailing has been utilized as temporary and permanent earth support for railroad and tunnel excavations and temporary shoring for bottom-level excavations [4]. Soil nailing is putting in closely spaced steel bars, or nails, to passively reinforce the existing ground without using post-tension. The nails are then covered in grout [5]. Shotcrete or concrete is also applied to the excavation

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face as construction moves upward to maintain continuity. When stabilizing current slopes or excavations, soil nailing is frequently utilized since top-t--bottom construction offers advantages over alternative retaining wall technologies. These soil-nail systems, which are primarily loaded with tensile stresses, are constructed at a slope of 10° to 20° below the horizontal and are used to support slopes of the soil and excavations [6]. A shotcrete facing is applied first. Finally, the shotcrete face is provided. Cement grout for soil nails usually has a water-to-grout ratio of 0.40 to 0.45 [7]. Cement grout protects nails from rust and strengthens the bond between soil and nails. Drill rigs with air or water flush, either rotary or percussive, are frequently used for boring holes. The first and last shotcrete faces, in addition to the soil nails, enhance the overall stability of the earth's mass. The principles of soil nails and other soil reinforcement elements like tieback anchors or geosynthetics differ based on their stress distribution in the composite system. When soil nails are embedded in the grouted soil mass, the resisting forces act along the length of the nail. Because the contribution of the interface shear tension at the grout-solute contact is determined by the comparative shift between the grout and the flocculated soil, soil nailing is a passive soil-reinforcing technology [8, 9]. Conversely, the tieback anchors serve as active soil reinforcements because they are not fully grouted. After the grout material has achieved strength, the free zone, or area that is not grouted, is pre-stressed to preload the tieback anchors and reduce soil or wall failure against sliding. Consequently, the anchor turns into an active system of composite soil; it witnesses the sliding failure due to the anchor, and the soil is independent of their relative movements. The geosynthetic reinforcement was kept tension-free during the application. The stabilizing effects of the geosynthetic strips originate from the stress mobilizations of the geosynthetic reinforcement because of the relative movement of the reinforcement and the soil mass, similar to the soil nailing mechanism [10]. Because they are inexpensive, quick to build, and effective on slopes in populated areas, soil nails have gained popularity over the past few decades as an alternative to more conventional stabilizing slopes. Axial stresses on the soil nail are mostly caused by the displacement of the critical soil stress above the slope's critical slip surface. Pull-out studies are generally executed to properly measure the maximum interface bonding and frictional behavior between the soil mass and treated soil or between the treated soil and the reinforcement member [11]. Simulating how a soil nail might behave when its surface is subjected to axial force mobilization makes it easier. The expected pull-out capacity is utilized per current design standards to specify the soil's nail pattern and the desired stability for the slope [12]. Analytical and semi-empirical methods are used to determine the pull-out capability. The amount of water in the soil, the saturation level, the kind of soil, the particles' size, the soil's dilatancy, the shear strength, and the testing methods are some of the variables that affect the complex pulling behavior of soil nails [13]. Therefore, a limited number of field pull-out tests are usually employed to validate the pull-out capacity of nails that have been assessed in a lab or computed analytically.

Many previous studies have assumed a horizontal slope crest, which is uncommon in real-world conditions. Additionally, only a few studies have considered the impact of back slope inclination. Most research has been focused on specific slope angles and nail configurations, resulting in a limited understanding of the combined effects of factors like slope angle, back slope inclination, nail inclination, layout, length pattern, and soil properties. This chapter provides an overview of soil nailing and emphasizes its importance while exploring the optimal layout for a soil nail system [14].

## SOIL-NAIL MECHANISM AND FAVORABLE CONDITIONS

The key process in soil nailing involves creating tensile stress within the soil nails as the structure moves laterally. This stress arises mainly from the friction between the steel bars and the soil mass, as well as the interaction at the nail head (see Fig. **1**). The maximum tensile force occurs when the nails intersect potential failure surfaces, dividing the reinforced soil into active and passive zones. The active zone, which is prone to detaching from the structure, generates frictional shear stresses on the nail surface, leading to a pullout force. As the active zone deforms downward, it causes axial displacement along the nails, which continues until the nail-soil interface reaches its maximum shear capacity.

The passive zone is the stable area behind the probable failure surface that prevents the reinforced system from failing. The two zones are fastened together by soil nails because the composite mass acts to prevent the reinforcements from pulling out (active and passive). The length of the earth's nails provides the necessary pullout resistance in this area. Unlike anchors, where the axial force created is constant over the free length, earth nails experience axial force variations along their length. As a result of slope deformations, the reinforcement is predominantly susceptible to tensile stresses combined with shearing and movements. However, the resistance to bending and shear provides a minimal contribution to the pulling capacity and can be ignored for practical reasons.

In a soil nail wall system, the potential failure plane can be envisioned as being inclined relative to the vertical, with $\alpha$ representing the inclination angle of the wall face relative to the horizontal. Initially, it may seem intuitive to consider the friction generated along a soil nail as the product of the vertical stress, the active length of the nail, and the soil's frictional resistance, expressed by the parameter tan□. The soil friction (Fi) is given by:

## CHAPTER 9

# Micropiles: Small-Diameter Elements for High-Strength Solutions

**Abstract:** Micropiles, with their slender diameters ranging from 10 to 30 cm, have become a cornerstone of geotechnical engineering, providing high-strength solutions for challenging structural support problems. Initially developed more than 50 years ago for postwar reconstruction complexities, the last two decades have seen a significant evolution in micropile technology, from low-capacity pile networks to the utilization of single, high-capacity elements for substantial structural support. Their effectiveness in enhancing bearing capacity and reducing settlement has been particularly noted in strengthening existing foundations. Whether vertically or in reticulated patterns, micropiles support excavations, slopes, and foundations and are indispensable in the underpinning or retrofitting of structures within confined spaces where traditional methods falter. The recent resurgence of interest in micropile networks, recognized for their technical and economic viability, extends their application to slope stabilization, lateral load accommodation, and seismic retrofitting. This chapter explores the advancements and broadening applications of micropiles technology, underscoring the innovative research and development that continue to expand their potential. It presented a comprehensive view of future advances and envisioned applications, illustrating the pivotal role of micropiles in addressing the intricate challenges of modern geotechnical engineering within a single cohesive narrative.

**Keywords:** Foundations.Micropiles, Reinforcement, Rehabilitation.

## INTRODUCTION

Micropiles were conceived in Italy in the early 1950s in response to the demand for innovative techniques to support historic buildings and monuments that had been damaged during World War II [1]. A reliable method was required to support structural loads with minimal movement and for installation in access-restrictive environments with minimal disturbance to the existing structure. An Italian specialty contractor called Fondedile and Fernando Lizzi developed the technique [1]. The use of micropiles has grown significantly and has been used mainly as foundation support elements to resist static and seismic loading conditions, as well as *in situ* reinforcements for slope and excavation stability [2, 3].

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Micropiles are placed more closely together than traditional pile foundations because they have a smaller diameter (approximately 90 to 300 mm) than piles [4]. A drilling technique appropriate for the soil/site conditions is used to drill the holes with casings. After the removal of the drilling rod and tools, reinforcement bars that are typically corrosion-resistant steel bars are then placed into the wells. The grouting is then carried out sequentially under pressure as the casing is gradually removed. Because micropiles typically require little equipment, the technology can be used in confined spaces with limited access. The application of micropiles has a very broad range; it can be carried out in spaces with little vertical clearance, such as basements and under bridge structures [5]. The interiors of commercial structures, tiny tunnels, mountain paths, rice fields, mountainous, forested areas, steep slopes, and other places are some crucial sites where micropiles can be installed. Additionally, micropiles can be inserted through existing foundations and used to support buildings, as well as to repair broken foundations [6].

Steel pipes and coated wood piles are sometimes used as affordable options in India to increase the carrying capacity of the foundation or maintain displacements to acceptable levels [7]. Similar techniques are frequently used to stabilize slopes and improve foundations. Using utilizing micropiles, a ten-story building, previously unstable due to differential settlement, was brought back to safety. The friction between the pile and the soil was used to develop corrective measures [8]. Galvanized steel pipes 100 mm in diameter and 10 m long with the bottom end closed with shoes were used.

Two unique scenarios are shown when the design and functional properties of micropiles are examined: In Case 1, micropiles are loaded directly, while in Case 2, micropiles are part of a reinforced soil mass that collectively supports the load, improving the resistance of the structure to pressure [9]. However, urban building frequently incorporates aspects of the two scenarios. The complex underlying terrain of contemporary cities, with many preexisting subterranean buildings, often needs help to place micropiles beneath foundations directly. Another strategy is to surround the foundation with micropiles, similar to both Case 1 and Case 2.

Numerous factors that impact the efficiency of micropiles in stabilizing attempts have been the subject of research [10, 11]. Research has shown that the reinforcement angle is essential when micropiles are placed next to foundation pillars because it can reduce settlement and increase soil stiffness [12]. Simultaneously, studies have shown a relationship between micropile length and vertical load-carrying capacity, indicating that longer micropiles provide more support [13, 14].

Closer placement of the micropile results in more significant benefits [15]. Bandyopadhyay *et al*. [16] found that this configuration lessens the movement of the lateral soil below the footing, improving the stability of the structure. The concept of unilateral installation of micropiles led to the strategic placement of micropiles for testing near square footing. These tests, aimed at identifying the most effective configurations that minimize settlement and maximize footing bearing capacity, thereby optimizing the benefits of micropile construction, examined the effects of several parameters, including micropile diameter, length, inclination, proximity to the footing's edge, and spacing.

## TYPES OF MICROPILES

Micropiles excel when conventional piling techniques face limitations such as tight spaces, environmental sensitivities, or around existing buildings. Their classification depends on their structural design, installation method, and grouting approach. The primary variants of micropiles include displacement and replacement piles.

### Displacement Piles

These piles are members that are driven or placed through vibration into the ground, thereby displacing the surrounding soil laterally during installation. Replacement piles are placed or constructed within a previously drilled well, thus replacing the excavated ground. A micropile is a small diameter (< 300 mm), drilled and grouted pile that is typically reinforced. Micropiles could be classified into two classes according to design uses [17]. Micropiles loaded axially or laterally are included in the first group. These micropiles either transmit structural loads to the competent strata beneath the foundation (for example, by underpinning structures) or can be employed to prevent the movement of failure planes (*i.e*., stabilization of slopes).

### Replacement Piles

The second category consists of micropiles that fortify the bulk of the soil by creating a reinforced soil composite. On the other hand, according to grouting methods, the micropiles can also be divided into four categories (Groups A, B, C, and D) (see Fig. **1**). The micropile grout is placed under gravity for group A. Group B uses pressure to inject grout into the hole. However, the pressure is restricted to prevent hydrofracturing of the surrounding soil. The installation procedure for group C micropiles entails two steps: first, a primary grout is applied under pressure to create hydrofracturing of the surrounding ground, and then, just before the primary grout hardens, a secondary grout is injected *via* a

## CHAPTER 10

# Securing Structures: The Strategic Use of Ground Anchors

**Abstract:** This chapter delves into using ground anchors in modern construction and civil engineering, highlighting their role in stabilizing and supporting natural and engineered structures. Ground anchors restrain movement by transferring tension to the ground *via* friction or adhesion at their interfaces. This chapter explains the fundamental design principles of ground anchors and their efficiency in utilizing *in situ* soil properties to provide vertical or lateral support. Having substantial advantages over traditional methods, such as rigid gravity retaining walls or external bracing systems, including cost reductions and accelerated project timelines, ground anchors have become increasingly prevalent in civil engineering projects over the past few decades. This discussion covers the technical aspects and applications of ground anchors and emphasizes their growing importance in the industry.

**Keywords:** Anchorage performance, Pull-out loading, Reinforced slope, Soil-anchor interface.

## INTRODUCTION

Over the past 50 years, permanently grouted anchors have been widely used to provide vertical and lateral supports for naturally occurring and constructed structures. The end-type anchorage, where the tendon is grouted below the probable slip surface, has been utilized owing to its major technical advantages, which lead to significant cost savings and a shorter construction period to stabilize hazardous slopes to a set safety factor [1]. The fundamental idea of the design is to use the friction generated at the interfaces between anchors to transfer the resisting tensile forces to the ground. Tendons are often anchored within the soil mass and tensioned at the surface against a bearing plate, concrete pad, or geosynthetics that are tensioned to develop loads [2]. Some documented instances of this technology have been successfully used to stabilize slopes. When a ground anchor is used for a temporary application, its service life typically ranges from two to five years, depending on the length of the building project [3]. In contrast, permanent ground anchors are used for the lifespan of permanent structures [4]. Ground anchors are used either permanently to reinforce and safeguard retaining walls, sloping terrain, dams, bridges, and basements or temporarily as part of deep excavation support systems. They are also intended to withstand lateral and uplift stresses caused by the wind [5, 6].

Furthermore, by lowering the horizontal displacements of structures, ground anchors stabilize landslides and prevent overturning [7]. Ground anchors are preferable to braced systems to maximize the working space and construction efficiency. Consequently, anchors shorten construction schedules and reduce costs [8]. Ground anchors fall into two primary categories: passive anchors, which become mobilized upon displacement of the held structure, and prestressed anchors, created by tensioning the anchors. Pre-tensioned ground anchors are structural components inserted into drill holes filled with grout and are intended to transfer an imposed tensile load into the ground. Prestressing the anchor is typically performed to shield the soil from tensile overload [9]. The choice between prestressed and passive anchors is influenced by several variables, including the displacement level of the anchor, the type of rock it will be placed in, and the corrosion risk [10].

Tendons comprised of prestressed strands or bars with a high yield point are necessary for the anchorage of structures and stabilization of slopes. Only anchors with a short service life, such as those used to secure rock surfaces in tiny subterranean excavations or in situations where prestressing is not preferred, are appropriate for bars made of low-quality steel. Although strands are more expensive than bars, their use has become popular. Compared to a tendon made of prestressed bars, a tendon made of prestressed strands is less likely to experience prestressing loss owing to ground creep [11]. To locate the tendon connection length outside the probable active zone, it is necessary to consider a minimum of 3 m [12, 13]. To prevent undesirable load reductions caused by sitting losses during load transfer and prestress losses due to creep in the prestressed tendon of the anchor or soil, the unbonded length must be larger than 3 m for bar tendons and 4.5 m for strand tendons [14]. Pullout tests were conducted by Hsu and Chang [15] on vertical anchors buried in a layer of gravelly soil [16]. Many findings showed that as the tendon bond length rose from 1.5 to 5.82 m, the ultimate load of the anchor increased from 215 to 883 kN [16].

Additionally, Juran and Elias [17] subjected prestressed anchors buried in stiff clay with tendon bond lengths of 4.6 and 9.2 m to pullout and creep tests. Their findings showed that anchors with shorter tendon bond lengths always had a reduced creep rate and higher ultimate strength. Furthermore, the stress was distributed beyond the structure using anchors with shorter tendon bond lengths [17].

## COMPONENTS OF GROUND ANCHORS

They are designed to stabilize and support natural soil or rock slopes to resist any horizontal or vertical movement. The design concept involves the transfer of resisting forces generated in the inclusion into the ground through friction/adhesion mobilized at the interface. A structural member inserted into soil or rock to transmit an applied tensile load into the earth is called a prestressed grouted ground anchor (see Fig. **1**).

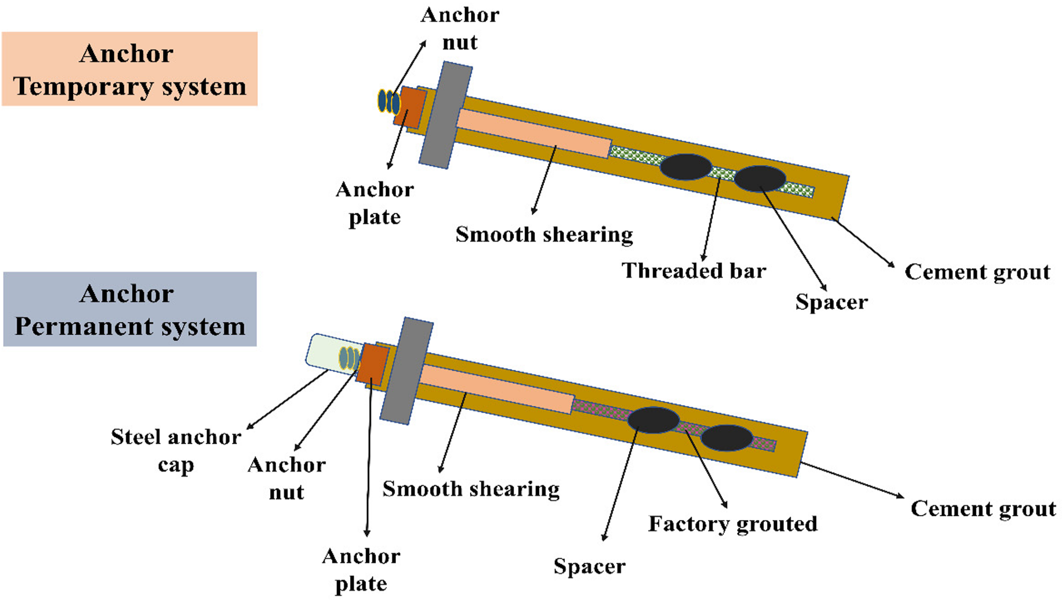

**Fig. (1).** Ground anchor system.

Ground anchors, also known as grouted ground anchors, are placed in drill holes filled with grout. Tiebacks are another name for grouted ground anchors. The anchorage, free stress (unbonded) length, and bond length are the three fundamental parts of a grouted ground anchor. The anchor head, bearing plate, and trumpet system, known as anchoring, can transmit the prestressing force from the prestressing steel (bar or strand) to the ground or the supporting structure.

1. Anchor head: connects the anchor to the supported structures, permitting stressing and locking off the prestressing steel.
2. Tendon: prestressing steel wires, strands, or bars. It transmits force from the anchor head to the fixed anchors.
3. Fixed anchor: transfer the anchor force into the ground.

## CHAPTER 11

# From Soil to Sustainability: Ground Improvement Methods for Achieving SDGs

**Abstract:** The need for sustainable development is prioritized in all infrastructure projects and frameworks being released by various statutory bodies. The utilization of ground improvement methods assumes a central role in this venture, providing novel approaches to enhance soil stability and functionality in accordance with environmental sustainability principles. This section delves into the correlation between ground improvement techniques and the pursuit of sustainable development goals (SDGs), emphasizing their contribution to a more sustainable and resilient infrastructure environment. Emphasizing the reduction of environmental impact, this discussion investigates the incorporation of sustainable ground improvement approaches that are in line with goals such as carbon emission reduction, advancement of the circular economy, and attainment of cost-effective, high-performance project results. SDG 9 - Industry innovation and infrastructure, SDG 11- Sustainable cities and communities, and SDG 12- Responsible consumption and production are primarily focused on cultivating an environmentally friendly society. Any infrastructure development endeavors must uphold sustainability, and ground improvement activities within these projects should also be evaluated from this perspective. Through the viewpoint of environmental conservation and financial feasibility, we scrutinize diverse ground improvement techniques that utilize both conventional and innovative methodologies, underscoring their capacity to tackle pressing issues like climate change mitigation, resource preservation, and eco-conscious construction practices. By presenting successful case studies and emerging patterns, this section seeks to elucidate the way forward for the integration of ground improvement methods as a fundamental component of sustainable development, ultimately aiding in the realization of the SDGs in an environmentally conscious and economically viable manner.

**Keywords:** Circular economy, Ground improvement techniques, Geoenvironment, SDGs.

## INTRODUCTION

As the planet grapples with the escalating impacts of climate change, the Earth's water cycle intensifies, altering precipitation patterns and increasing the prevalence of extreme weather events, such as floods and droughts. Concurrently, global wind speeds are accelerating, and coastal areas face the compounded challenges of shifting temperature extremes, altered frost depths, and the signi-

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ficant threats posed by rising sea levels [1]. These climatic shifts are reshaping the landscape of civil engineering and demanding innovations in the design, construction, and maintenance of infrastructural projects [2]. The escalating force of water necessitates more robust flood defenses and erosion control measures, whereas the uptick in heat waves calls for adaptive building materials and energy-efficient cooling systems to mitigate soaring energy demands [3, 4]. Climate change compels a re-evaluation of engineering standards, including load capacities and foundation specifications, to safeguard against weather-induced structural failures and disasters. The construction sector, a notable contributor to global environmental pressures, faces a dual challenge: it must not only adapt to the changing climate but also mitigate its substantial ecological footprint, which is characterized by significant waste production, resource extraction, energy use, and greenhouse gas emissions [5 - 8]. Industry activities are linked to widespread environmental degradation, including issues such as eutrophication, atmospheric pollution, ozone depletion, and overexploitation of water resources [9, 10].

In response to these pressing concerns, the United Nations' 2030 agenda for sustainable development, with its 17 SDGs, provides a comprehensive framework for steering the global community towards a more sustainable future. The construction industry is pivotal in achieving several of these goals, particularly those related to sustainable cities and communities, affordable and clean energy, industrial innovation and infrastructure, responsible consumption and production, and climate action [11]. The principles of the circular economy (CE) have emerged as a transformative approach for the construction sector, promising to address about ten SDGs by promoting the reuse and recycling of materials, thus reducing waste and environmental impact [12]. Fig. (**1**) shows the circular economy framework of materials. Minimizing environmental impacts is a fundamental aim of the CE. However, applying CE principles alongside environmental assessments has highlighted profound gaps in research, particularly in the construction industry [13]. Implementing CE strategies within construction only automatically ensures more sustainable processes and materials [14]. Furthermore, simply reducing material use in construction does not guarantee environmental benefits such as reduced energy consumption or lower greenhouse gas emissions. This oversight emphasizes a critical shortfall in current frameworks, which need more comprehensive methodologies for evaluating the environmental repercussions of CE practices in construction. As CE principles are adopted throughout various sectors, the urgency for detailed, industry-specific environmental impact assessments becomes more apparent, especially within the construction field [15].

Ground improvement techniques are at the forefront of this transformation, offering sustainable solutions that minimize environmental harm while enhancing soil stability and structural durability. By integrating innovative materials and methods such as geosynthetics into ground improvement practices, civil engineers can significantly reduce the carbon footprint of their projects and harness waste from other industries, turning challenges into opportunities for sustainable development [16]. This chapter explored the role of ground improvement techniques in advancing sustainability within the construction sector, highlighting their potential to contribute to a more resilient and environmentally friendly future.

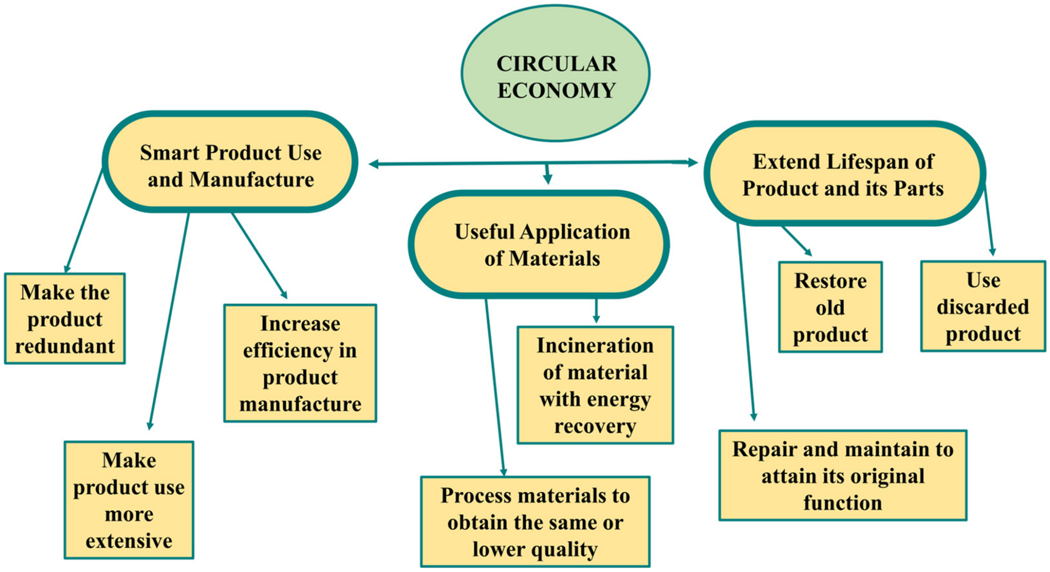

**Fig. (1).** Circular economy framework of materials.

## LINKING UN SDGS AND TARGETS TO GROUND IMPROVEMENT METHODS

To fully understand how ground improvement approaches contribute to achieving the SDGs of the United Nations, a methodical mapping exercise is required. This method examines the alignment between the 169 SDG targets and associated indicators with the knowledge, abilities, and actions about ground improvement. Prior mapping projects across several fields have yielded frameworks that can be modified and implemented for ground improvement. Fig. (**2**) shows the SDGs proposed by the United Nations.

Johnsson *et al*. [17] explained a methodology that offers a comprehensive understanding of the relationship between construction operations and SDG targets. This methodology, when adapted, provides a valuable tool to map ground

# SUBJECT INDEX

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