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Mechanisms and Mitigation of Soil Settlement in Soft Ground Construction

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ABSTRACT

Soft soils, characterized by low shear strength, high compressibility, and high-water content, present significant challenges in construction, often leading to excessive settlement and potential structural failure. Settlement is defined as the deformation of soil due to applied stresses. The primary mechanisms driving soft soil settlement include primary consolidation, where pore water pressure dissipates under sustained loading, and secondary compression. The rate of consolidation is influenced by factors like natural variability of the ground and soil permeabilities. Since soft soils are often unavoidable in construction, steps must be taken to enhance their strength to allow for safe and stable development. This paper explores three widely used ground improvement methods: preloading with Prefabricated Vertical Drains (PVDs), geosynthetics, and deep soil mixing (DSM). The usage, limitations, and feasibility of each method are discussed in detail to provide insights into effective mitigation strategies for soft ground construction.

Keywords: Soft Ground, Soil Settlement, Consolidation, Vertical Drain, Geosynthetic

INTRODUCTION

Construction on soft ground poses significant challenges in geotechnical engineering due to the inherent weakness of soil soils. The stability of civil engineering structures depends on the geotechnical properties of the foundation, such as shear strength, permeability, and soil compressibility [1]. Soft soils are characterized by high compressibility, high water content, low permeability, and low shear strength. These properties often result in engineering problems, including slope instability, bearing capacity failure, and excessive settlement during or after construction. Among these issues, soil settlement is the primary engineering challenge encountered in construction on soft ground [2]. To address the challenges posed by soft soils, geotechnical engineers have developed various ground improvement techniques aimed at mitigating settlement and enhancing the stability of foundations. Techniques such as preloading with vertical drains, deep soil mixing, and geosynthetics are commonly employed to accelerate consolidation, improve shear strength, and reduce deformation under applied loads. This study explores the mechanisms of soil settlement in soft ground and evaluates the effectiveness of various mitigation techniques through case studies and comparative analysis.

Mechanisms of Soil Settlement in Soft Ground Construction

Soil settlement in soft ground construction is a complex process influenced by the interactions between applied loads and soil properties. It comprises three primary mechanisms: immediate settlement, primary consolidation, and secondary compression. Immediate settlement takes place as soon as a load is applied. It is caused by the elastic deformation of soil particles. This mechanism is more prominent in granular soils, but cohesive soils with some stiffness can also experience immediate settlement. In saturated soils with low permeability, immediate settlement occurs at a constant volume because the pore water cannot escape quickly. This deformation is primarily due to shear strains beneath the loaded area, with minimal drainage due to the low permeability of soil [3].

Primary consolidation occurs over time and is the dominant mechanism in soft clays. It results from the gradual dissipation of excess pore water pressure caused by sustained loading. As water is expelled from the voids, the soil's void ratio decreases, leading to a reduction in volume. The rate of primary consolidation depends on factors such as soil permeability, thickness of the compressible layer, and drainage conditions. Terzaghi's consolidation theory explains the time-dependent nature of this process and highlights the importance of pore water dissipation in settlement [3].

Secondary compression begins after primary consolidation is complete. It is driven by the long-term creep behavior of soil particles under a constant load. This mechanism involves the rearrangement of soil particles and the gradual closure of voids. Unlike primary consolidation, it is independent of pore water dissipation. Secondary compression is significant in organic soils and highly plastic clays, where deformation can continue indefinitely [3].

Preloading with Vertical Drains

Preloading with Vertical Drains is a widely used ground improvement technique that accelerates soil consolidation in soft ground construction. The method involves applying a temporary surcharge load (preloading) to compress the soil and installing Prefabricated Vertical Drains (PVDs) to provide vertical drainage paths for the release of pore water. This combination effectively reduces settlement time, which would otherwise take years due to the low permeability of soft soils like clay. Additionally, this method offers multiple advantages, including accelerating the primary consolidation process, reducing the surcharge load required to achieve the same degree of consolidation within a given period, and enhancing soil shear strength through soft soil consolidation [4]. Over the years, PVDs have been effectively employed in numerous projects across Asia and the world [5, 6, 7-10].

Preloading induces a significant portion of the ultimate settlement expected after construction [11, 12]. Prefabricated vertical drains (PVDs) are synthetic geosynthetic elements with an inner drainage core and a geotextile filter [6]. They are used to shorten the drainage path within the soft soils to accelerate the primary consolidation process [13]. According to [14], the preloading process increases the load on the soil, compressing it and expelling excess pore water, which facilitates consolidation and reduces potential settlement. Meanwhile, vertical drains enhance this process by promoting the dissipation of pore water pressure, allowing for faster settlement and improved ground stability. Together, preloading and vertical drains provide an efficient and effective solution for mitigating settlement in soft soil construction projects.

Case Studies

Case Study 1 - Runway Construction: Analysis of Settlement Prediction Using PVDs and Preloading

A runway construction project in Indonesia demonstrated the effectiveness of preloading combined with Prefabricated Vertical Drains (PVDs) in mitigating settlement on soft clay soils (Figure 1). Without PVDs, achieving 90% consolidation would have taken approximately 10 years, but with PVDs and preloading, the settlement time was significantly reduced. By referring to Table 1, it revealed that installing PVDs at 1-meter spacing achieved 90% consolidation in just 79 days compared to 202 days for 1.5-meter spacing and 390 days for 2-meter spacing. PVDs were installed at a depth of 11 meters using a triangular configuration to ensure uniform consolidation. The study concluded that closer PVD spacing (1 meter) was the most efficient, reducing settlement time and improving soil stability. This case highlights the importance of optimized PVD design and placement for effective ground improvement.

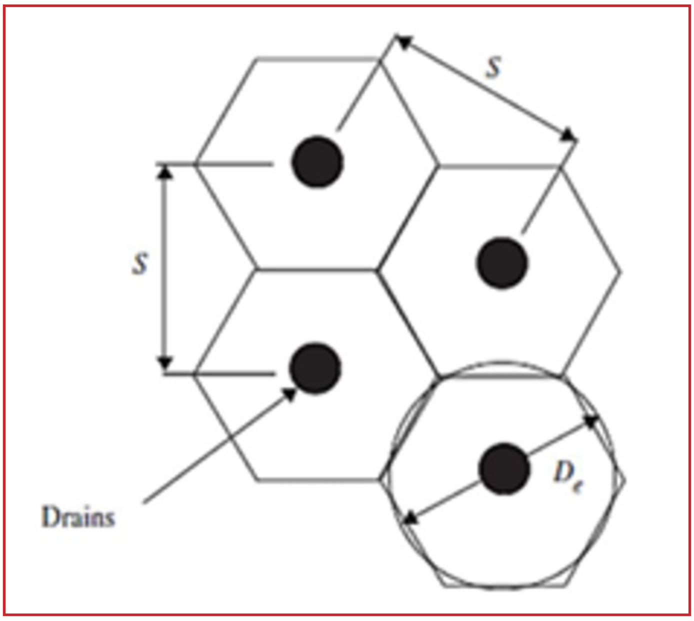


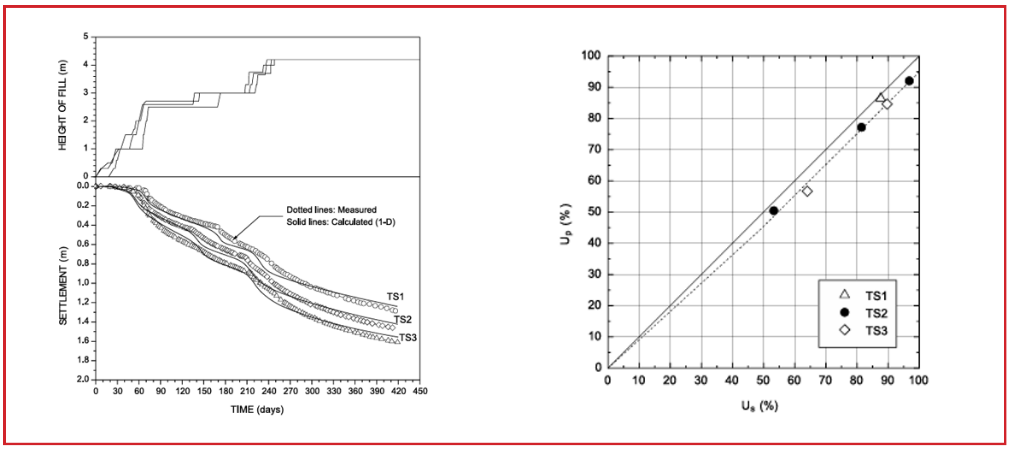
Figure 1. PVD Triangle Configuration [13]

Table 1. Time for soil consolidation [14]

S (m)	Uh(%)	t (years)	t (days)
1	0.9	0.22	79.36
1.5	0.9	0.56	202.59
2	0.9	1.07	390.44

Case Study 2 – New Bangkok International Airport (NBIA): Preloading with PVDs

The New Bangkok International Airport (NBIA) project in Thailand showcased the effective use of preloading with Prefabricated Vertical Drains (PVDs) for improving soft Bangkok clay. Three test embankments (TS1, TS2, TS3) were constructed with PVD spacings of 1.5 m, 1.2 m, and 1.0 m. The TS3 embankment with 1.0 m spacing demonstrated the fastest consolidation and the most significant shear strength improvements, highlighting the efficiency of closer PVD spacing. Figure 2 shows the comparison of measured and calculated settlement, and degree of consolidation of embankments TS1, TS2 and TS3, while Figure 3 shows the rate of settlement and field vane shear strength of TS3. Field monitoring confirmed that settlements and shear strength predictions aligned well with measured data (Figure 4), validating the reliability of preloading and PVDs. This case study illustrates how optimized PVD spacing and predictive.



(a) (b)

Figure 2. Comparison of (a) measured total settlement and calculated 1D settlement and (b) degrees of consolidation from settlement and pore pressures [5].

Deep Soil Mixing

The Deep Soil Mixing (DSM) method is an advanced in-situ soil treatment technology widely used to improve weak or compressible soils in soft-ground construction (Figure 5). This method involves blending the in-situ soil with cementitious binders to create high-strength soilcrete columns or panels. By employing this method in construction projects, settlement issues can be greatly reduced, enhancing ground stability. DSM is widely used to improve the bearing capacity of soils [15], reduce settlement [16], and mitigate risks such as liquefaction in soft and saturated soils [17]. According to [18], the DSM method

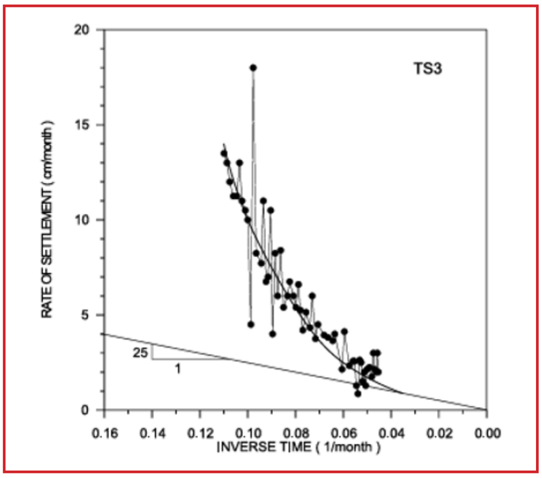


Figure 3. Rate of settlement versus inverse time plot for embankment TS3 [5]

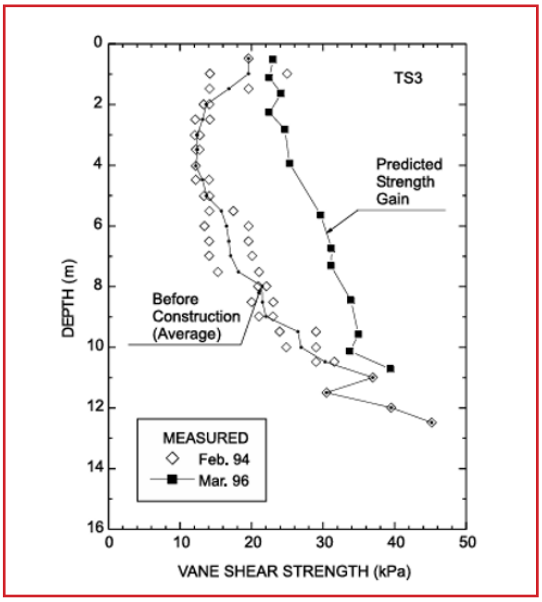


Figure 4. Field vane shear strength measured below embankment TS3 [5]

originated in the USA in the 1950s, gaining global recognition, particularly after the 1990s. DSM has become popular because it generates minimal noise and vibration, offers improved accessibility of equipment, is easy to implement, relies on readily available materials, and benefits from the involvement of numerous contractors [19,20]

In the DSM process (Figure 6), in-situ natural soil is mechanically mixed with binders, which can be either slurries (wet method) or powders (dry method). The dry method is ideal for cohesive soils with high moisture content (60-200%) and uses dry binders such as lime or cement. In contrast, the wet method injects slurry binders, which are primarily cement-based, to produce more homogenous columns [21]. However, in soils with high water content, the wet method may face some limitations. This is because the elevated water-to-binder ratio can result in lower strength [22]. DSM columns or panels are usually arranged in square or triangular grids to control settlement and increase load-bearing capacity. According to [18], the diameter of the columns varies from 0.6 to 1.5

meters, and CDMA [23] states that they can reach a depth of up to 45 meters. This configuration distributes loads evenly and helps stabilize soft soils. As a result, differential settlement issues can be greatly reduced.

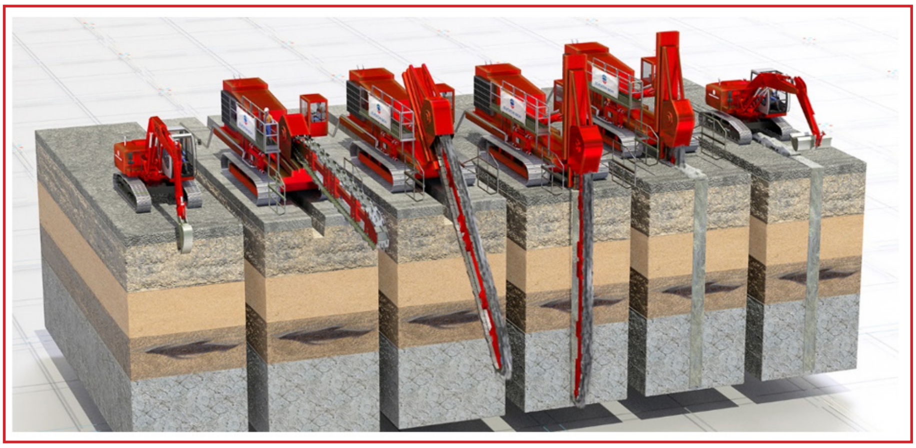


Figure 5. Deep soil mixing (DSM) process illustration

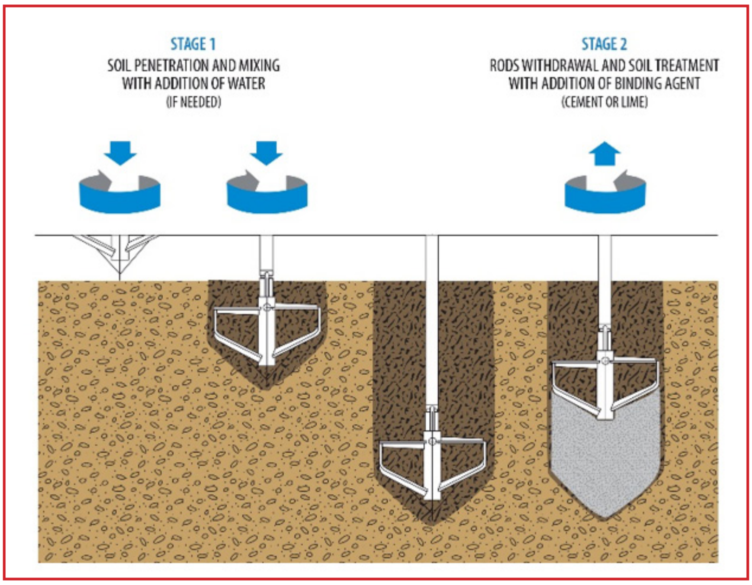


Figure 6. Stages of the deep soil mixing (DSM) process

Case Study 1 – Boston Central Artery/Tunnel Project (Big Dig)

The Boston Central Artery/Tunnel Project (Big Dig) serves as a prominent example of using DSM to stabilize soft clay soils for large-scale infrastructure construction (Figure 7). This project involved improving the soil's shear strength and stiffness by mixing in-situ soils with cementitious binders to form soil-cement columns. DSM columns were installed to depths of 20–30 meters in a grid pattern, providing uniform reinforcement across the soft soil layers beneath the tunnels and highways. The technique successfully mitigated settlement risks by significantly enhancing the soil's load-bearing capacity and reducing compressibility [24]. As a result, the DSM method ensured the structural stability of the project while meeting the challenges posed by urban construction in constrained spaces.

Figure 7. Soil mixing ground support on Boston Big Dig, Central Artery Tunnel Project

Case Study 2 – Kansai International Airport

The Kansai International Airport was constructed on an artificial island in Osaka Bay, Japan. This case study represents a significant example of ground improvement on soft marine soils. During its second phase of development, Deep Soil Mixing (DSM) was employed alongside other techniques to stabilize the weak Holocene clay layer and reduce settlement (Figure 8). The DSM method involved mixing in-situ soil with cement milk to form improved soil-cement columns, which were arranged in wall-type and lattice-type patterns as shown in Figure 9. This arrangement helps enhance the shear strength and stability of the foundation.

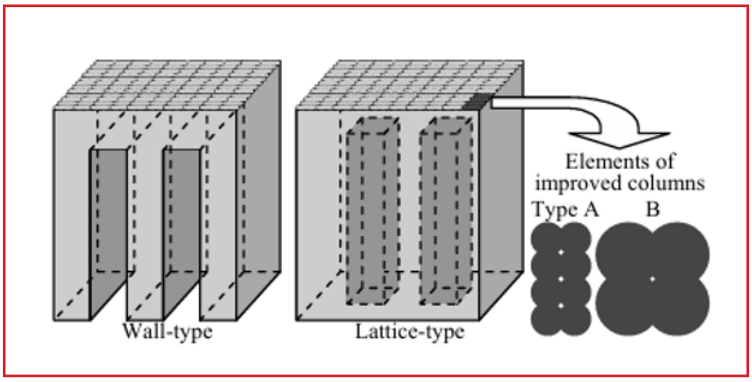


Figure 8. Image of improvement patterns in the deep mixing method [25]

Approximately 330,000 cubic meters of soil were treated using DSM during this phase. The project also incorporated sand drain and sand compaction pile methods to complement DSM as shown in Figure 9. These techniques helped accelerate consolidation and contributed to the long-term stability of the foundation. By integrating these methods, the settlement of the Holocene clay was completed during the reclamation phase. This approach enabled the artificial island to develop in a controlled and uniform manner. Moreover, predictive modelling tools were employed to estimate long-term settlement

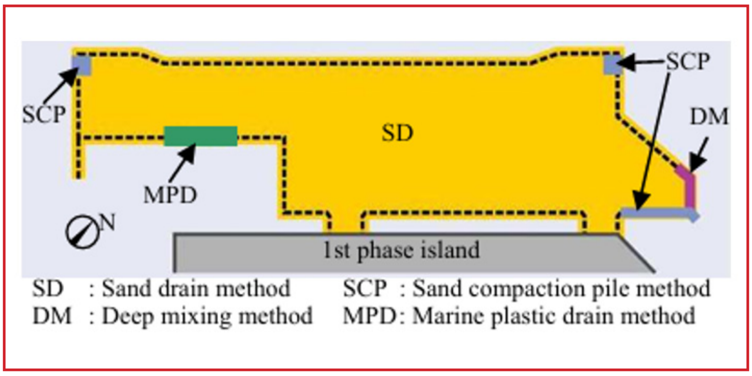


Figure 9. Ground improvement techniques applied in the second phase of construction [25]

for deeper Pleistocene clay layers. In short, this case study demonstrates the effectiveness of DSM and complementary ground improvement methods in mitigating settlement risks for large-scale infrastructure on challenging soft marine soils.

Geosynthetics

Geosynthetics are materials that can be used to mitigate the effects of settlement. Geosynthetics such as geogrids or geotextiles can be used as basal reinforcement in embankments constructed on soft ground [26]. The geosynthetics are able to achieve this by mobilizing their tensile strength when used in the soil layers which enhances the stability of the embankment. If the foundation deforms excessively due to lack of mobilised tensile strength in the reinforcement, rotational slip failure can occur [27]. With the geosynthetics taking a majority of the load, the overall bearing capacity of the embankment can be improved.

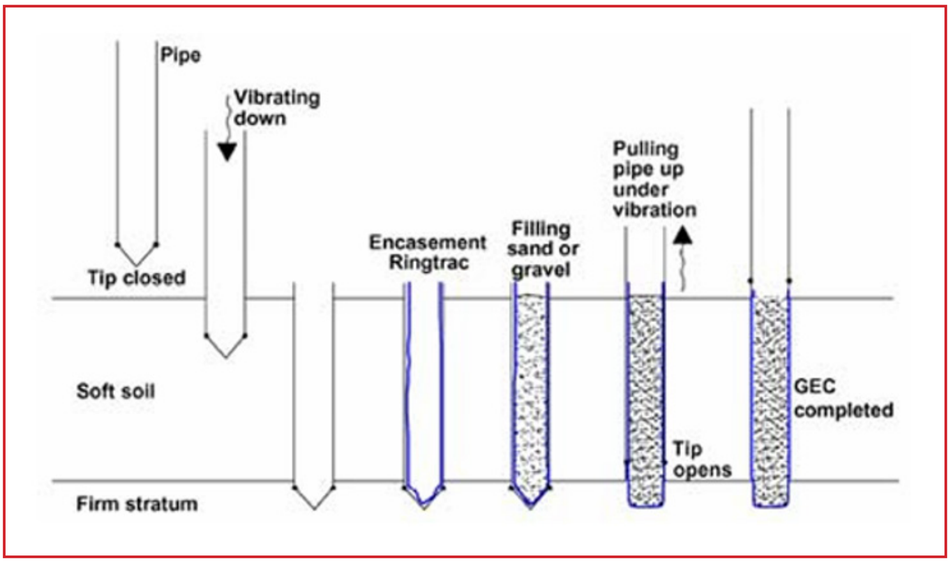


Figure 10. Installation of GEC columns using the displacement method [26]

Typically, in soft ground, stone columns can be used to reinforce the strength of the surrounding soil. For the stone columns to work properly, the surrounding soils need to be categorized as soft soil and above (>15kPa) [28]. In cases where the soils are considered to be very soft soil, the surrounding soils do not provide enough confinement so a geosynthetic encased column (GEC) can be applied. This technique was first developed in Germany [29, 30]. GEC can be constructed using 2 methods which are, the displacement method and the replacement method. The displacement method is shown in Figure 10 [26]. The replacement method for geogrid geogrid-enclosed stone column (GESC) is shown in Figure 11 as proposed by [27]. The difference between the 2 methods is that the replacement method is typically used for soils with higher penetration resistance.

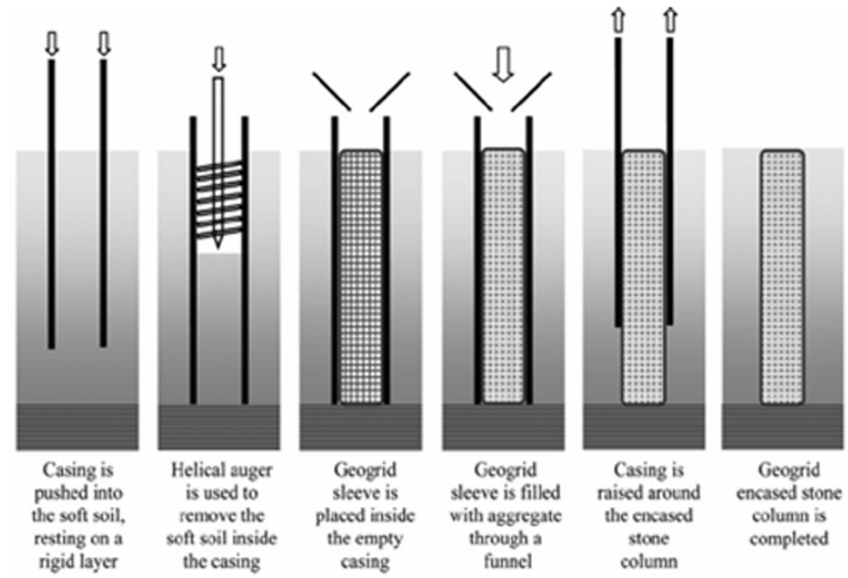


Figure 11. Installation of GESC using replacement method [27]

With the addition of geosynthetics, the stone column is still able to expand and displace nearby sand thus allowing for the stone column to work as it should under normal situations. Secondly, the geosynthetics also allow for water drainage from nearby soft soils which ends up strengthening the soil even further. Few studies have been carried out regarding the working mechanism and performance of the geosynthetic reinforced stone columns. For example, [28] conducted model tests to compare geosynthetic stone columns (GSC) with normal stone columns and found that the geosynthetic stone column had higher capacity than normal stone columns. Murugesan and Rajagopal [31] conducted further research and found that the stiffness of the GSC increases with the tensile strength of the geosynthetic used. To consider the benefits provided by the geotextile confinement, procedures were adopted from Raithel and Kempfert [32] and Kempfert and Raithel [33]. Generally, all three methods have their own merits for improving the soft soils to allow for construction (Table 2).

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Table 2. Comparison of three methods for improving the soft soils to allow for construction

Criteria	Preloading with Vertical Drains	Deep Soil Mixing	Geosynthetics
Mechanism	Uses surcharge load and PVDs to accelerate pore water dissipation and consolidation.	Mixes soil with binders to form stronger soil-cement columns [21].	-Uses geotextile or geogrids to improve the bearing capacity of the foundation. -Geotextile can hold stone columns to allow for the nearby very soft soil to be displaced.
Efficiency	-Speeds up the draining process but still require time for water to drain out until acceptable levels. -Reduces consolidation during and post-construction -Improves the bearing capacity of soils before construction.	-High efficiency in improving soil strength and stiffness [24]. -Provides immediate improvement in load-bearing capacity [15].	-Effective at strengthening soft soil for embankments. -For stone columns, it can only control settlement not eliminate especially in very soft soils.
Cost	-Cost for soils may be high depending on availability. -Cost is typically low but may have some unexpected costs due to delays.	High initial costs due to specialized equipment and materials.	-Geotextiles can be expensive depending on the type used. -Requires machinery to construct the GECs. -May be expensive to do soil replacement for GEC.
Applications	Effective in soft clays and silts with high water content [4].	Effective for soft marine clays, loose fills, and peat [24].	Can be used even in very soft soils but needs to have columns at fixed spacings throughout the development.
Environmental Feasibility	-Requires excavation to obtain large amounts of soil for preloading. -PVD will be removed once completed so not big environment impact.	-Additives are confined within the soil, reducing the risk of contamination. -Uses non-toxic binders and reuses in-situ soil, reducing the need for material transportation [21].	-Results in a lower carbon footprint [21]. -Produces lower greenhouse gas emissions [34, 35].
Limitation	-Initial soil conditions need to have some amount of permeability otherwise the water will still take a long time to drain out [14]. -Availability of fill material.	-Ground vibrations and noise may affect surrounding areas. -High costs and requires specialized equipment and expertise [7].	-If soils deform excessively, the tensile strength of geosynthetics cannot be fully mobilized. -Requires vertical settlement of columns to mobilize tensile strength.

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Conclusion

For preloading with vertical drains, it is the best when applied when the development requires an increase in reduced level. The reason for this is that since we are already required to buy soil to build the embankment, it would be more efficient to use PVD to speed up the overall process of consolidation. However, if there's no need for an embankment then this method would be wasteful in terms of cost and time. The height of the embankment will also need to be considered as it can't be built up very high if the initial strength of the soil is weak. For geotextiles, it can be used to increase the bearing capacity of foundations. On its own it is not very effective as it requires that the soil not deform too much but that may be difficult to achieve in very soft soils. It can be paired with the preloading and PVD method to improve the strength of soil. Another use of geotextiles would be to act as a 'sock' for stones in a stone column. If the soil is resistant to penetration, soil replacement would have to be used which is significantly more expensive than soil displacement method. The geotextile stone columns would only be required in very soft soils otherwise, a normal stone column would suffice. For deep soil mixing method, it is a high-cost solution but offers significant advantages in improving the shear strength and stiffness of weak soils. It is particularly effective for soft marine clays or highly compressible soils, providing immediate load-bearing capacity and minimizing settlement risks. To sum up, the choice of method depends on the specific project requirements, including soil conditions, budget, and the type of construction. Combining methods, where feasible, can often enhance overall effectiveness and provide a more sustainable solution to challenges in soft-ground construction.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Jee Rou Ni: validation, data curation. **Darren Liew Yeong Chun:** methodology, investigation. **Dayang Zulaika Abang Hasbollah:** writing-original draft preparation, supervision. **Bakhtiar Affandy Othman:** writing-reviewing and editing. **Fazleen Slamat:** visualization, validation. **Muhammad Adib Adam Mat Nor:** investigation, methodology.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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