

# Advancements in Ground Improvement Techniques for Soft Soils

M. Husaini<sup>1</sup>, K. W. Gan<sup>1</sup>, D. Z. Abang Hasbollah<sup>2\*</sup>, B. A. Othman<sup>2</sup>, F. Slamet<sup>2</sup>, M. N. Abdurahman<sup>3</sup>, R. Bhatawdekar<sup>4</sup>

<sup>1</sup>Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia

<sup>2</sup>Centre of Tropical Engineering, Universiti Teknologi Malaysia, Johor Bahru, Malaysia

<sup>3</sup>Slope Engineering Branch, Headquarters of the Public Works Department of Malaysia, Sultan Salahuddin Road, Kuala Lumpur, Malaysia

<sup>4</sup>Indian Institute of Technology Kharagpur, India

**ABSTRACT** - Ground improvement techniques are essential for enhancing the engineering properties of soft soils, which is typically characterized by low shear strength, high compressibility, and poor drainage characteristics. Over the years, several ground improvement methods have been developed and applied to mitigate the challenges posed by soft soils in construction projects. This paper presents a comprehensive review of the most widely used techniques for soft soil improvement, including deep mixing, jet grouting, preloading, and vertical drains. Each method is evaluated in terms of its feasibility, cost-effectiveness, application areas, and efficiency. Case studies from various regions are examined to highlight the practical implementation of these techniques in real-world scenarios, with particular attention to their performance in improving soil strength, accelerating consolidation, and reducing settlement. The findings indicate that while each method has its strengths and limitations, a combination of techniques often yields the best results, depending on site-specific conditions. This paper concludes by recommending optimal approaches for the use of ground improvement techniques based on soil characteristics, project scale, and environmental considerations, ultimately contributing to safer and more sustainable construction practices in soft soil environments.

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## 1. INTRODUCTION

Soils, such as clay, peat, and silts, pose significant challenges in engineering projects due to their low shear strength, high compressibility, and poor drainage characteristics [7], [9]. These properties complicate the ability of these soils to support heavy structures, leading to issues such as excessive settlement, instability, and damage to the constructed infrastructure [1], [3]. To overcome these challenges, ground improvement techniques are widely used to enhance the mechanical properties of the soil, providing better foundation stability and reducing settlement [1], [10]. These methods work by improving soil strength, reducing compressibility, and enhancing drainage, thereby making the site more suitable for construction [11], [12].

Ground improvement techniques vary in terms of their approach, depth of influence, cost, and effectiveness Horpibulsuk et al., 2017, [2]. Among the most commonly used techniques for stabilizing soft soils are Deep Mixing, Jet Grouting, Preloading, and Vertical Drains [5], [6]. Each technique offers unique advantages and is suitable for different site conditions and project types [1], [8]. This review will provide detailed case studies of these techniques, followed by a comparison of their effectiveness and a conclusion regarding their applicability in soft soil stabilization.

## 2. CASE STUDIES

### 2.1 Deep Mixing (Tokyo Bay Reclamation, Japan)

#### Feasibility:

Deep Mixing is particularly well-suited for large-scale projects where soil improvement is required at significant depths. The feasibility of this technique is high when deep stabilization is needed, especially for projects involving soft, deep, or highly compressible soils. In the case of the Tokyo Bay Reclamation Project, which involved building an airport on reclaimed land, this method was chosen for its ability to stabilize deep soft clays up to 30 meters deep [15]. However, one of the challenges is the specialized equipment required, including soil-mixing rigs that can drill deep into the ground to mix the soil with binding agents like cement or lime. (Bhardwaj et al., 2015). While the technique works effectively for large-scale infrastructure projects, its feasibility decreases in smaller projects or where access to the site is limited. The method is labour-intensive and requires considerable time and effort to mobilize the necessary machinery, which adds to both complexity and cost.

**Application:**

In the Tokyo Bay Reclamation project, Deep Mixing was used to treat large areas of soft clay and provide stability to the ground, preventing excessive settlement under the weight of new construction. The process involved mixing the soft, deep soil layers with cement-based materials (lime or cement slurry), effectively forming cemented columns within the soil. This improved the soil's shear strength, reduced compressibility, and minimized the risk of excessive settlement [15]. This method is commonly applied in similar contexts, such as large-scale land reclamation projects, industrial facilities, or heavy infrastructure developments like airports or bridges, where the foundation must be stabilized to support significant loads. Deep Mixing is capable of treating deep layers that would otherwise be difficult to address with surface-level techniques, making it a powerful tool in ground improvement for complex, deep soil stabilization.

**Cost:**

The cost of Deep Mixing is relatively high due to several factors. First, specialized equipment is required to drill and mix the soil at considerable depths. Second, the materials used—primarily cement or lime—add to the expense. For the Tokyo Bay project, costs ranged from \$100 to \$250 per cubic meter, with deeper or more challenging soil conditions leading to higher costs [6]. The overall cost of a project utilizing Deep Mixing can be quite substantial, especially in large-scale reclamation or construction projects. However, despite the high upfront costs, the long-term benefits of reduced settlement and increased soil stability can justify the expense, particularly in projects where maintaining structural integrity over time is critical.

**Efficiency:**

Deep Mixing is highly efficient in improving the shear strength and stability of soft soils, but its efficiency can be slow due to the deep mixing process and the curing time required for cement or lime to set and achieve full strength. The technique typically results in an increase in soil strength of up to 300%, drastically reducing settlement over time [15]. While Deep Mixing provides excellent long-term results in terms of reducing settlement and improving load-bearing capacity, the process is slow compared to other methods. In the case of the Tokyo Bay Reclamation project, this delay in implementation was balanced by the method's effectiveness and the project's need for deep soil stabilization. The results, however, were highly efficient in terms of providing a solid foundation for the airport infrastructure, reducing risks of future settlement after construction.

**2.2 Jet Grouting (Soekarno-Hatta International Airport Expansion, Indonesia)****Feasibility:**

Jet Grouting is a very feasible method for stabilizing soils in urban or confined areas, where space limitations or existing structures might make other methods impractical. This technique was employed successfully in the Soekarno-Hatta International Airport Expansion in Indonesia, where soft peat and clay layers were problematic for construction [16]. It is particularly effective in areas where deep stabilization is needed but where access is constrained or where other methods, such as deep mixing, would be too costly or impractical. The feasibility of Jet Grouting in such environments is high due to its ability to treat localized areas without the need for large-scale excavation or disruption of surrounding infrastructure. The technique can be used in confined spaces, offering a solution for urban construction projects or areas with existing infrastructure where traditional ground improvement methods may not be possible.

**Application:**

In the Soekarno-Hatta Airport expansion, Jet Grouting was employed to stabilize the soft peat and clay soils that were prevalent at the site. The method involves injecting high-pressure grout (often a cement-based slurry or a mixture of grout and additives) into the soil to create solidified grout columns. These columns improve the soil's shear strength and reduce its compressibility, making the ground more suitable for heavy construction [16]. Jet Grouting is commonly used for soil stabilization in urban environments, as well as in foundations for buildings, bridges, or other infrastructure projects where soil conditions are poor. It is particularly useful when dealing with soft or loose soils like peat, sand, or clay, and where other methods might not be as effective or feasible.

**Cost:**

The cost of Jet Grouting is moderate to high, depending on several factors including the depth of treatment, soil conditions, and the materials used in the grout. For the Soekarno-Hatta project, the cost ranged from \$50 to \$150 per cubic meter, which is significantly higher than preloading but more cost-effective than deep mixing in many cases [16]. The cost is driven by the need for specialized equipment, high-pressure grout injection, and the cost of the grout itself. While the method can be costly, it is still considered a more cost-effective option compared to deeper methods like deep mixing, particularly in areas where localized soil stabilization is needed, and the scale of the project is smaller or more constrained.

**Efficiency:**

Jet Grouting is known for its relatively quick results. It is more efficient than Deep Mixing in terms of the time required to implement and complete the treatment. The process of creating grout columns and curing them can typically be completed much faster, which makes Jet Grouting a preferable choice for projects on tight timelines [16]. The technique

can improve soil strength by 50% to 100%, which helps to reduce settlement and increase the load-bearing capacity of the soil. However, the precision required in the injection of the grout is critical to its efficiency—too much or too little grout can result in uneven treatment and reduced effectiveness. In the Soekarno-Hatta case, the method resulted in significant improvements in soil strength and stability, which was crucial for the successful expansion of the airport.

### 2.3 Preloading (Changi Airport Expansion, Singapore)

#### Feasibility:

Preloading is highly feasible in areas with soft, compressible soils, such as at the Changi Airport Expansion in Singapore, where significant areas of land were underlain by soft clay. Preloading works best when the goal is to accelerate the consolidation of soft soils before construction begins [13]. The technique involves applying a surcharge load—typically a temporary embankment or fill material—over the area to simulate the future weight of the structure and induce settlement of the soil.

Conventional preloading is a widely used ground improvement technique aimed at enhancing the bearing capacity and reducing settlement of soft soils. This method involves applying a temporary load to the ground surface, which compresses the underlying soil layers, expelling pore water, and increasing soil density. The process accelerates consolidation, thereby improving soil strength and stability before the construction of permanent structures. The load remains in place until the target consolidation is achieved. As stated by [26], this is the simplest and most traditional preloading technique, where a temporary surcharge load (e.g., sand or gravel) is placed on the ground to accelerate consolidation, by increase the total stress or reduce the pore water pressure. The weight of the surcharge induces excess pore water pressure, which dissipates over time, causing the increase in the effective stress of the soil to consolidate. This method is highly effective for clay-rich soils with low permeability.

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#### Application:

At Changi Airport, preloading was applied to accelerate the consolidation of soft clay deposits, which were at risk of excessive settlement due to the weight of new structures. The technique was applied by placing temporary surcharge loads over the ground to induce the settlement of the soil before construction. Once the desired level of settlement was achieved, the surcharge material was removed, and construction could proceed on stable soil.

Vacuum preloading is commonly used to enhance the engineering characteristics of freshly deposited marine clay slurry because it is more energy-efficient and environmentally friendly [29], [30], [31], [32]. The traditional vacuum preloading technique employs atmospheric pressure as a temporary surcharge, utilizing prefabricated vertical drains (PVDs) to shorten drainage paths and expedite soil consolidation. This method is often more cost-effective and efficient compared to conventional surcharge preloading methods [33]. Vacuum preloading applies negative pressure to soft soils, creating an atmospheric surcharge effect. A sealed membrane covers the treatment area, and prefabricated vertical drains (PVDs) expedite the dissipation of pore water. This method has been extensively used in marine and reclaimed land projects due to its efficiency and environmental benefits. The vacuum preloading system includes vertical drains, horizontal vacuum pipes placed in a sand layer, membranes, and vacuum pumps. This configuration is depicted in Figure 1.

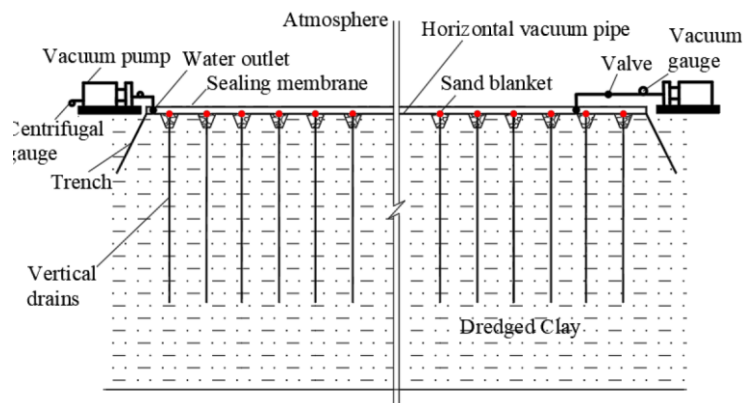


Figure 1. Vacuum preload system [33]

The process of preloading can be illustrated using a spring analogy (Figures 2 and 3). When a surcharge load is applied, negative pore water pressure develops within the soil. Although the total applied stress remains constant, the suction effect increases the soil's effective stress. As pore pressure dissipates (Figure 3), the spring compresses, representing an increase in the soil skeleton's effective stress. This uniform rise in effective stress reduces lateral movement and lowers the risk of shear failure, even during rapid embankment construction. Consequently, a smaller surcharge fill may be sufficient to achieve the desired settlement [14], [36].

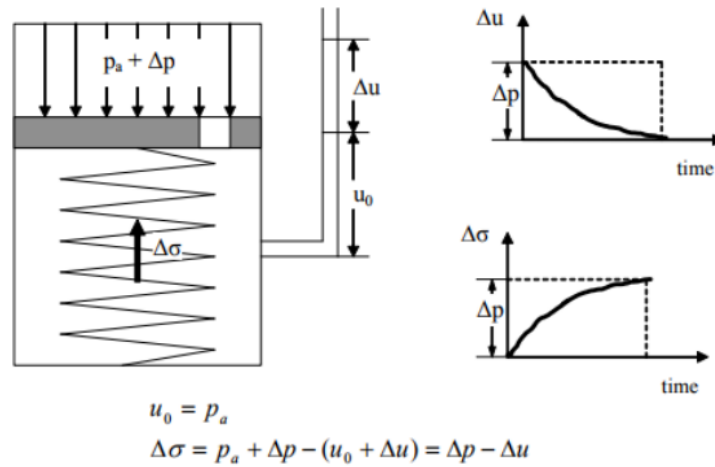


Figure 2. Surcharge load in spring analogy [33]

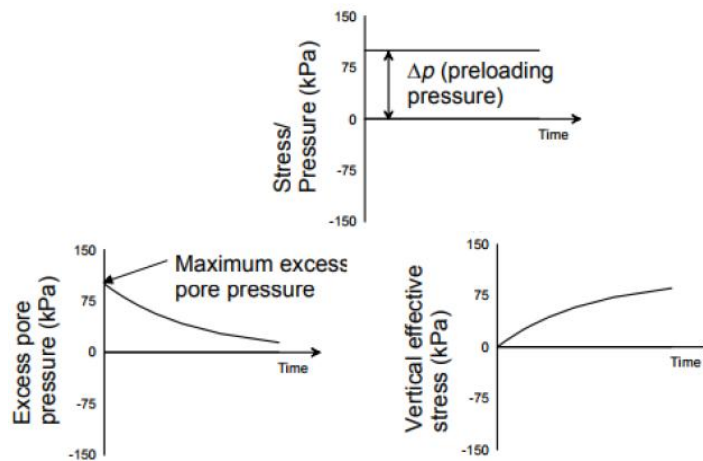


Figure 3. Preloading consolidation process [36]

**Cost:**

Preloading is one of the most cost-effective ground improvement methods, as it primarily involves the construction of temporary embankments or surcharge materials, which are relatively inexpensive compared to other methods like deep mixing or jet grouting. The main cost of preloading lies in the preparation of the surcharge load and the monitoring of the soil's settlement over time. Costs typically range from \$10 to \$50 per cubic meter, depending on the volume of settlement that needs to be induced and the duration of the process. While it is a cost-effective method, the primary limitation is the time required for consolidation, which can delay the overall project timeline [13].

**Efficiency:**

Preloading is an efficient technique for reducing settlement in soft soils, but it is slow compared to other methods. The consolidation process can take several months or even years, depending on the depth of soft soils and the magnitude of the surcharge load. In the case of Changi Airport, preloading allowed for significant consolidation of soft clays but required careful monitoring to ensure that the soil settled evenly, and that no differential settlement occurred. Table 1 presents a summary comparison of the engineering properties of the soil before and after the ground improvement using pre-compression method. The evaluation focuses on the soil's shear strength ( $S_u$ ) and compressibility parameters, including  $C_c$ ,  $e_o$ , and  $C_v$  [37]. The enhanced bearing capacity resulting from preloading is evident in Table 2. Notably, a substantial improvement in bearing capacity is observed with preloading at a surcharge height exceeding 13 cm, with the carrying capacity increasing by 101% to 242% [38]. Advanced computational tools, such as Plaxis 2D and 3D finite element models, enable accurate predictions of settlement, pore pressure dissipation, and overall soil behaviour during preloading [49], [50]. These models help in optimizing designs and mitigating risks.

Table 1. Soil properties prior and after vacuum preloading [37]

Soil properties	Prior to improvement	After improvement
$S_u$	(6 - 30) kPa	67kPa
Average	10kPa	
$C_c$	0.2 – 0.6	0.3 – 0.36
Average	0.5	
$e_0$	0.5 – 1.5	1.04
$C_v$	(6-21) $m^2/yr$	(2.11 – 3.64) $m^2/yr$

Table 2. Bearing capacity prior and after vacuum preloading [38]

Height of embankment (cm)	Bearing capacity, $q_u$ (kPa)	Improvement of $q_u$ (%)
0	2.64	0
1.6	3.13	19
3.3	3.35	27
6.5	3.69	40
13.1	5.29	101
26.1	9.01	242

For the case study done by [39] to improve the soft, saturated clayey layers beneath the oil storage tanks in the Mahshahr project, the preloading method was evaluated. This technique was applied to accelerate the consolidation settlement rate by using an embankment. Additionally, soil settlement under the oil tanks was compared before and after preloading, based on modified soil parameters, as shown in Figure 4. The settlement results were plotted, showing that embankment construction continued for 108 days, during which a waiting period of 53 days allowed the soil beneath the embankment to reach 95% consolidation. At this point, the soil's final settlement reached 122.2 cm, and the interstitial water pressure had minimized, signalling the end of the consolidation period. Following this, the soil exhibited slight inflation, and upon removing the embankment, the final settlement decreased to 102 cm, indicating that soil flow occurred as the embankment was removed. After the tanks were placed and left for 30 days, the soil experienced an additional 9 cm of settlement, reaching the final consolidation level.

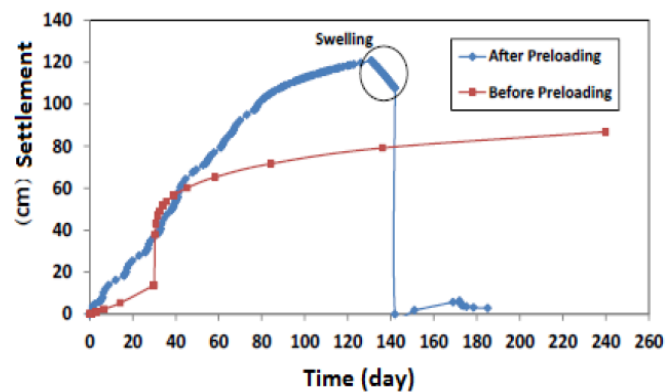


Figure 4. Ground settlement analysis using Plaxis 3D [39]

Some studies have indicated that vacuum preloading achieves greater consolidation and less settlement compared to surcharge preloading [40], [41], [42], [43]. Consolidation settlement consists of immediate, primary, and secondary settlements, with the immediate and primary stages largely completed during preloading. However, when the soil serves as a foundation in the operational phase, secondary consolidation continues due to creep in soft soil under prolonged stress. This uneven settlement during the service phase can compromise structural safety and potentially damage buildings. Therefore, examining how vacuum and surcharge preloading influence immediate, primary, and secondary settlements is crucial for minimizing uneven secondary settlement and its adverse impacts on building safety. Nevertheless, the effects of these methods remain insufficiently explored.

Based on study of [44] the improvement work conducted on soft soil ground in Zhuhai City within the Pearl River Delta, a comparative analysis of vacuum preloading and surcharge preloading was undertaken. The key findings are as follows:

- i. Vacuum preloading is more effective than surcharge preloading in terms of reducing consolidation time and settlement. However, surcharge preloading is associated with smaller secondary consolidation settlements, which makes it preferable for minimizing settlement during the service phase.

- ii. The primary consolidation settlement ( $S_{pt}$ ) reaches approximately 90% of the total consolidation ( $S_p$ ), driven by changes in excess pore water pressure ( $u_e$ ). In vacuum preloading, pressures drop below  $-40$  kPa, whereas in surcharge preloading, the pressure typically ranges between 20 kPa and 25 kPa.
- iii. An increase in strata permeability coefficient leads to greater consolidation degrees but has minimal impact on the overall consolidation efficiency.
- iv. Vacuum preloading is superior for reducing uneven settlement, whereas surcharge preloading offers better performance in managing ground settlement during operational service.

#### 2.4 Vertical Drains (Port of Brisbane Expansion, Australia)

Vertical Drains are highly feasible for use in soft, compressible soils with high water content, making them ideal for projects like the Port of Brisbane Expansion, where the ground consisted of thick soft clays. The primary advantage of vertical drains is that they accelerate the consolidation of soft soils by providing a direct path for water to escape, thus significantly reducing settlement time. The feasibility of this technique depends on the specific soil conditions at the site. Vertical drains are most effective in areas with high water tables and deep layers of compressible clay. The technique may be less effective in very deep or dense soil layers, where other methods may be required [14].

##### Application:

At the Port of Brisbane, vertical drains were installed to accelerate the consolidation of soft clays. These drains allowed excess pore water to escape, which accelerated the natural consolidation process. Vertical drains are often used in conjunction with preloading to further speed up settlement and reduce the time required for construction [14]. PVDs are also used together with the vacuum preloading method to distribute vacuum pressure and facilitate the dissipation of pore water. Therefore, PVD techniques become part of the core technologies in the fill surcharge or vacuum preloading methods. Prefabricated Vertical Drains (PVDs) typically comprise a core and filter made from various materials, loosely assembled and detachable. Liu and Chu (2009) developed features an adhered core and filter, enhancing discharge capacity and tensile strength compared to conventional PVDs.

In vacuum preloading projects, circular PVDs have been employed to boost consolidation efficiency. Additionally, PVDs crafted from biodegradable polymers have been introduced, as noted by [46]. To enhance stiffness and expedite pore pressure dissipation, the University of Wollongong developed cross-shaped and hollow cylindrical PVDs, as Figure 5 shown. Preliminary analyses indicate that cross-shaped PVDs expand the drainage influence zone by approximately 10% [47]. In railway track settings, where band drains are installed longitudinally, these larger-diameter PVDs can be positioned beneath concrete sleepers to optimize subgrade consolidation and shear strength [48].

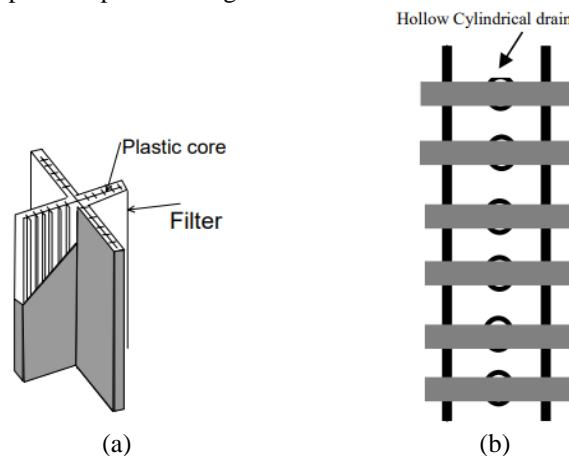


Figure 5. (a) Cross-shape PVD, (b) Hollow cylindrical drain [47]

##### Cost:

Vertical drains are relatively cost-effective compared to other ground improvement methods, such as deep mixing and jet grouting. The cost is typically associated with the drilling process and the materials used to construct the drains, such as synthetic wick drains [14]. Costs typically range from \$10 to \$40 per meter of installation, depending on factors like depth, soil conditions, and the spacing of the drains. While the costs are low compared to methods like deep mixing, the overall cost of the project will increase if the area of land requiring treatment is large.

##### Efficiency:

Vertical Drains are highly efficient in reducing the consolidation time of soft soils. When combined with preloading, vertical drains can reduce settlement time by 50% or more, allowing for faster project completion. The installation of vertical drains allows for accelerated pore water escape, which leads to quicker consolidation and more stable ground [14]. In the case of the Port of Brisbane project, the use of vertical drains allowed for rapid consolidation of soft clay layers, which helped ensure the stability of the port's foundations. This method is especially effective when used in combination with other techniques like preloading to optimize efficiency.

## Comparisons on Case Studies

Table 3. Comparison of the case studies in the respective factors

Factor	Deep Mixing (Tokyo Bay Reclamation, Japan)	Jet Grouting (Soekarno-Hatta International Airport Expansion, Indonesia)	Preloading (Changi Airport Expansion, Singapore)	Vertical Drains (Port of Brisbane Expansion, Australia)
Feasibility	Suitable for large-scale projects requiring deep soil stabilization; high feasibility for soft, deep soils.	Highly feasible in confined urban spaces or areas with soft soils; challenging in densely built areas.	Feasible in areas with soft, compressible soils; requires large areas for surcharge.	Feasible in soft, compressible soils with high water content; works best in coastal or port areas.
Soil Conditions	Soft, deep, highly compressible soils (e.g., clay) at depths of 10-30 meters.	Soft, compressible soils like peat or clay, often in urban environments.	Soft, compressible clay or highly saturated soils.	Soft, compressible clays with high water tables (common in coastal regions).
Application	Used for stabilization of soft clays in large infrastructure projects like land reclamation (e.g., Tokyo Bay Airport).	Used to stabilize soft soils in confined spaces (e.g., Soekarno-Hatta Airport expansion).	Applied to reduce settlement and accelerate soil consolidation before construction (e.g., Changi Airport).	Used to accelerate consolidation of soft clays, often combined with preloading (e.g., Port of Brisbane).
Main Process	Mixing soil with cement or lime at depths to create stabilized columns.	High-pressure grout injection to create solidified columns in soil.	Surcharge load applied to induce settlement, allowing for natural consolidation of soft soils.	Installation of vertical drains to allow water escape, accelerating consolidation when combined with preloading.
Cost	High cost: \$100-\$250 per cubic meter due to specialized equipment and materials (cement/lime).	Moderate to High cost: \$50-\$150 per cubic meter due to high-pressure equipment and grout materials.	Low cost: \$10-\$50 per cubic meter; primarily associated with surcharge construction.	Low cost: \$10-\$40 per meter of installation; cost-effective compared to deeper techniques.
Time for Implementation	Slow process: Time-intensive due to deep mixing, equipment mobilization, and curing times (months).	Moderate speed: Faster than deep mixing but still requires precision and can be time-consuming.	Long duration: Consolidation takes months to years, depending on surcharge load and soil conditions.	Fast process: Can accelerate consolidation significantly when combined with preloading; faster than preloading alone.
Efficiency	Highly efficient in increasing soil strength (up to 300%) and long-term stability. However, the process is slow.	High efficiency in stabilizing soils and reducing settlement, but precise grout injection is crucial for effectiveness.	Moderate efficiency: Reduces settlement over time, but the process is slow and may delay the overall project.	High efficiency: Speeds up consolidation, reducing settlement time by 50% or more when used with preloading.
Longevity / Performance	Excellent long-term performance reduces settlement and increases load-bearing capacity over time.	Offers long-term soil improvement, though grout columns may be subject to degradation if not applied properly.	Provides long-term stability once settlement is achieved; however, the process is not quick.	Provides long-term performance when combined with preloading, preventing excessive settlement in soft soils.
Environmental Impact	Moderate environmental impact: Potential for increased dust and noise from machinery; concerns regarding cement leaching in groundwater.	Moderate to high environmental impact: High energy consumption from the use of high-pressure grout injection.	Low environmental impact: Limited use of materials and equipment; temporary surcharge materials are removed after settlement.	Low environmental impact: Minimal disruption, especially if the drains are installed using non-invasive methods.
Suitability for Large-scale Projects	Very suitable for large reclamation or infrastructure projects where deep soil stabilization is needed.	Suitable for urban projects and confined spaces where localized soil stabilization is required.	Suitable for large-scale projects with soft soil conditions requiring consolidation before construction.	Very suitable for projects in soft, compressible soils such as coastal, port, or large infrastructure developments.
Site Accessibility	Requires significant access for large machinery; less suitable for areas with space limitations.	Works well in confined spaces and urban settings, making it ideal for densely built environments.	Requires space for surcharge material placement; less feasible in tight spaces.	Can be implemented with minimal disruption and requires access for drilling rigs, but generally adaptable.
Adaptability to Site Conditions	Highly adaptable to deep, soft soils where other methods may not reach.	Moderately adaptable: Can handle a variety of soft soils, but precision in grout application is key.	Less adaptable: Most effective in uniformly soft, compressible soils; not suitable for highly variable ground conditions.	Highly adaptable: Effective in a wide range of soft soils, especially with high water content and in conjunction with preloading.

Table 4. Decision matrix for selecting ground improvement techniques

Criteria	Deep Mixing	Jet Grouting	Preloading	Vertical Drains
Soil Type	Deep soft clays (10–30 m)	Soft peat, urban clay	Soft compressible clays	Soft clays with high water table
Cost Effectiveness	Expensive, justified for large-scale projects	Moderately costly, suitable in constrained areas	Most cost-effective for soft clay	Cost-effective when combined with preloading
Project Duration	Long (months, curing time)	Moderate (weeks–months)	Long (months–years)	Fast when combined with preload
Best Use	Large-scale reclamation, airports	Urban/constrained sites	Large areas, cost-driven	Coastal/port, time-sensitive

Advancements in ground improvement techniques, including Deep Mixing, Jet Grouting, Preloading, and Vertical Drains, have transformed the practice of soil stabilization in soft and compressible soils. Each method presents distinct advantages depending on project-specific conditions. Deep Mixing is particularly effective for large-scale projects that require deep stabilization and provides long-term performance, although it is associated with high costs and extended implementation time. Jet Grouting offers greater speed and adaptability in urban or confined environments, but it requires precise execution and is generally more expensive than conventional methods. Preloading remains the most economical option for reducing settlement; however, its effectiveness is constrained by the long duration required to achieve consolidation. Vertical Drains, especially when combined with preloading, constitute an efficient and cost-effective approach for accelerating consolidation in coastal and port developments. The selection of an appropriate technique should be guided by soil characteristics, project scale, cost considerations, and time constraints, with integrated approaches often delivering the most balanced outcomes in terms of efficiency, economy, and long-term stability.

## CONCLUSION

Ground improvement techniques such as Deep Mixing, Jet Grouting, Preloading, and Vertical Drains have substantially advanced the management of challenges associated with soft, compressible, and unstable soils. Each method has distinct advantages and limitations, with their applicability determined by factors including soil conditions, project scale, cost considerations, and time constraints. While individual techniques can be effective, integrated approaches that combine multiple methods often provide superior outcomes, balancing efficiency, economy, and long-term stability. The findings of this study highlight that a tailored selection of techniques, informed by project-specific requirements, remains essential for achieving safe, durable, and sustainable construction on soft soils.

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## DATA AVAILABILITY STATEMENT

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

## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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