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# Improvement of the soft soil by cement column: Review Study

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**ABSTRACT**

Deep mixing technology is used to improve the engineering properties of soil. In this review, previous studies on the properties and problems of weak soils were collected and explained, focusing on silty soils found globally and locally. The study also includes a discussion of physical and chemical improvement methods, specifically (cement columns). The advantages of deep mixing technology are also covered from an engineering and economic point of view, as well as its relationship to the environmental impact, as it is one of the sustainable development techniques due to its use of environmentally friendly materials. In addition, one of the objectives of this research is to study the methods of adding cement, whether in the form of powder (dry method) or mortar (wet method). A comparison was made between them to clarify the advantages and disadvantages. It was found that what distinguishes the use of the dry method from the wet method is that the former is more common. The method's effectiveness depends on the soil's moisture content, so the technique is ineffective in soils with less than 30% water content. As cement hydration produces a cementitious gel (CSH) that binds soil particles together, leading to early strength gain, pozzolanic reactions cause increased shear strength and decreased soil compressibility. Finally, some recommendations are included in this article to understand the behavior of cement columns in improving soil and avoiding problems.

## 1. Introduction

Silty soils, in their softened state, are considered collapsing soil. These soils are unstable under the influence of loads, or some changes occur in their moisture, which often leads to their collapse under the influence of their weight. Voids within the internal structure of silty soil cause many problems for engineering facilities built on such soils, which sometimes end in structural deformation. [1][2].

Silty soils are often hydrophobic, creating challenging conditions for adequate moisture during compaction. They are susceptible to moisture, and their stability is greatly affected by

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the repeated drying and wetting cycles. They also exposed to shrinkage and cracking, affecting the strength of the erected structures as they attempt to rearrange their particles leading to downward movement in the foundations (i.e., foundations settlement). In many situations, the deformation of the wet subgrade is often a problem during construction, as well as under regular vehicle traffic loads[3][4].

Soils, classified as silty soil, generally consist of sand and silt with a small percentage of clay and binders. This is one of the most critical problems facing geotechnical engineers because it is susceptible to water. There are many types of collapsible soil, such as loose sediments, which are large deposits of silt resulting from the decomposition of various minerals such as feldspar, mica, and calcite. These sediments appear in their general form to be cohesive, but their structure quickly collapses when exposed to water. Silty soil is found near beaches, river edges, or the borders between desert areas and agricultural lands. This soil is characterized by its round grains due to erosion factors; from the above, these soils appear extremely dangerous when exposed to loads, which makes it necessary to treat them and improve their properties to avoid damage to the structures built on them. Numerous methods exist to improve them, such as deep mixing, dewatering, compaction, grouting, preloading with or without vertical drains, deep densification, stone columns, and soil reinforcement. Research on enhancing this soil has concentrated chiefly on lowering predicted settlement, raising soil-bearing capacity, and lowering building costs[5]. The deep mixing approach is one of the techniques for strengthening weak soils that has acquired worldwide traction. At the site, soft soil is stabilized without compaction through a binder. The deep mixing method (DMM) is usually applied to improve fine clay and organic soils for multiple objectives, such as stabilization, settlement reduction, excavation support, and seepage control. The deep mixing technique was first created in Sweden and Japan in the middle of the 1970s[6].

The deep mixing method involves stabilizing the soil at a deep depth, where lime or cement is either wet or dry, and mixing it with the soil on-site using a mechanical or rotary mixing tool. Deep-mixing columns resemble stone columns. It reduces expected settlement through soil reinforcement that transfers loads to the more solid layers instead of the topsoil on the site, whose properties will be improved. However, the main difference between them is that the strength of stone columns depends on the aggregate's friction angle and its confinement in the surrounding soil, while deep mixing columns have an internal strength of cohesion[5].

The spread of cement column technology in the world in improving the properties of weak soils has encouraged researchers to conduct many studies of this technology and to proceed with its application on the ground. The most important objectives of this study can be summarized as follows:

1. Providing scientific and engineering references with concepts for improving the engineering properties of weak soil using the cement soil column method.
2. Demonstrating the advantage and efficiency of this technology in improving the engineering properties of weak soils (Especially silty soil) spread locally and globally.
3. Comparing the application of this technology using cement mixing columns with soil in the powdered state (dry method) and cement in the slurry state (wet method) as shown in Table No. 1.

## 2. Methodology

### *2.1.Collecting research articles*

The objective of this paper is to investigate all the available studies about improving soil properties by using cement columns. The research process in this study focused on modern scientific research dealing with practical and theoretical aspects published after the year 2000 and up to the present. Initially, weak soils were discussed in general with the intention of silty soils; studies and research also represent the shape of an inverted pyramid to reach the desired goal, which means the knowledge gap between using cement in cement columns as a dry powder or as a slurry cement solution. Finally, the scientific papers collected were represented as papers reviewed by experts and referees and published in several sobriety journals.

**Table 1.** A comparison between the dry method and the wet method

| Dry method | Wet method |
|---|---|
| Cement is used as a powder and mixed with the soil outside or during the excavation and casting of the column. It may need to be pressed during the process of implementing the columns. | Cement is used as a mortar (slurry) and mixed with the soil during the shaft drilling, and high air pressure is required. |
| Implementing columns with large diameters up to 1.5 m and lengths up to 40 m. A homogeneous column can be obtained without distortion of the surrounding soil. With increased pressure, swelling and distortion may occur in some aspects of the surrounding soil. | The diameters of the columns range from 0.5 m to 0.9 m, and the lengths reach 45 m. Due to the pressure, it is impossible to obtain a homogeneous column, and it may affect the surrounding soil and cause swelling or displacement of the soil or column from its location. |
| It requires less equipment to implement, produces lower vibration levels, causes little or no damage, and does not require pre-mixing, thus being cost-effective. | The equipment is more expensive, and the vibration and noise levels are somewhat high. Damage occurs, and the method requires pre-mixing to prepare the mortar, which increases the cost. |
| One sustainable development technique uses environmentally friendly materials with little or no pollution when mixing and implementing columns and drilling. Still, the on-site mixing and ionic and pozzolanic interaction in the presence of moisture in the soil may lead to pollution and the emission of carbon dioxide gas. The appropriate moisture content must be available in the soil to complete the reaction process, not less than 30% for ion exchange and the interaction of cement compounds with soil elements. | It is one of the sustainable development techniques because it uses environmentally friendly materials and causes little or no pollution due to the ionic and pozzolanic interaction of cement compounds with the soil. |
| The method has given good results in reducing soil settlement, increasing bearing capacity, seismic loads, and liquefaction-prone soils. It has been widely used worldwide in many projects that require treatment, improvement, and reinforcement in soft and fine granular soils. | |

### *2.2. The style and the purpose of the study*

Initially, the research papers were sorted to suit the research of this article, as some of the papers collected were not relevant to the specific topic. After an in-depth reading of many of them, research questions were identified regarding the subject of this article by emphasizing papers directly related to this study. Table No. 2 shows the most important studies related to the topic of this study. Cement is one of the most essential and effective chemicals for improving silty soil properties. It increases the resistance of these soils and reduces their settlement through a series of chemical reactions in the presence of suitable conditions for the interaction, including water. For this reason, cement was chosen by this study as the stabilizing material to improve silty soil's properties at great depths, to check its efficiency as a stabilizer, and to identify the best methods for its implementation mechanism on site.

## 3. View on the weak soils

Durability is defined as the ability of stabilized soil to retain its strength, impermeability, and dimensional stability over a long period under the designed conditions[7]. The approximate classification of the entire soil in the world is divided into either clay or sandy soil. The latter does not pose any problem due to water seepage, mainly due to its formation from the parent material, rock. Otherwise, clay-type soil is formed by chemical weathering, which involves chemical reactions that form hydration, carbonation, and leaching. Due to these interactions, clay soil swells when it comes into contact with water and shrinks when it loses water. The majority of clay soils (fine-grained) in the world often pose swelling and shrinkage problems, and hence, they are often referred to as weak soils or soft soils, which is the main reason behind this quality. Clayey soil comprises various clay minerals such as smectite, attapulgite, chlorite, hallosite, illite, and the primary mineral, montmorillonite. Swelling and shrinkage problems lead to differential settlement[8].

Weak soils have other problems besides swelling and shrinkage, such as compressibility and collapse potential in soft soils such as clay, silt, and peat. These soil deposits are often found near river mouths and under swamps or lakes. They are frequently found to have high organic content or to be situated in prone seismically active regions, resulting in settlement and liquefaction during periods of intense ground movement. The Japanese earthquake that struck Niigata in 1964 is a prime example. In this instance and during the earthquake, several structures on loose saturated sand deposits collapsed more than one meter. At the same time, other buildings, primarily residential ones, were turned on their sides. However, when these weak, collapse-prone soils are left dry, they seem stable and substantial, but upon wetting, they consolidate quickly, causing large, frequently unanticipated settlements. Loose, set, and naturally burned are the two fundamental features of weak soil deposits. The main component of sedimentary soils is a cement structure formed like a honeycomb, loosely packed with silt-sized particles. They maintain the cohesiveness of a soft soil structure with trace levels of water-softening or water-soluble cementing agents, such as CaCO3 and clay minerals. When water is added, the silt particles' bonds disintegrate or become softer, enabling them to collect more thickly under all loading conditions. Due to their "loose" structure, sedimentation processes are typically responsible for their creation. Silty soils are deposited by gravity or water and are typically deposited in a saturated and loose manner. The capillary feature of this soil pulls copious amounts of moisture to the places of contact between the soil grains when water eventually drains from it. Minerals left in the soil at the locations where water evaporates bind the soil together[9].

Soft soils tend to deform and cause stability problems. They lack sufficient strength and stability to support engineering structures and change in size unevenly when exposed to environmental influences, such as changes in water content. For instance, in the particular case of the soft clay-grain soil of the Grati region in Indonesia, it causes a dike measuring 10.2 m. to settle as a result of consolidation, amounting to 1.896 meters due to the soft soil, which has low shear resistance value, soil's natural moisture level was almost at the fluid limit[10]There are regions worldwide where soft soil is widely distributed in coastal areas. Iraq is located mainly in the southern region between Basra and Al-Faw, and the lack of sufficient cohesion leads to many engineering problems in structures built on it.[11].

**Table 2.** Some research conducted on soil improved by cement columns

| Authors Names | Locations | Soil Type | Conclusions |
|---|---|---|---|
| Kempfert, (2003). | Germany | Different soils | The basic principle of using different column techniques, including cement, is to improve the soil and reduce the load without changing the soil structure. |
| Chai et al., 2009 | Japan | Loose sand | A modified method was proposed to predict the lateral displacements of the soil modified by installing cement soil columns. |
| Farouk and Shahien, 2013 | Egypt | Silty sand | Settlement can be reduced by 80% depending on the number and length of cement soil columns used to improve the soil. |

| | | | |
|---|---|---|---|
| Rayamajhi et al., 2015 | Japan | liquefiable sand | Strengthening liquefiable soil using cement soil columns in a centrifuge test case study. The soil is exposed to earthquake movements and sine waves. |
| Ahmad et al., 2015 | Malaysia | Clay | In this study, the optimization area and models of rigid and flexible foundations reinforced with cement soil columns are compared regarding the failure behavior of the deep mixing method. |
| Sukpunya and Jotisankasa, 2016 | Thailand | Soft clay | Using cement soil columns and slip circle analysis, the internal stability of the soil was ascertained, and a weighted shear equation utilizing the created big, straightforward, direct shear device was suggested. |
| Sedighi, Schweiger and Wehr, 2017 | Austria | Loose sand | Determining crucial locations where cement columns may fracture and assessing the impact of soil improvement's breadth and depth on the ground's reaction to seismic loads. |
| Pham et al., 2017 | Australia | Clayey-sand | The application of thermogravimetric tests and analysis to determine the extent of deterioration of cement soil columns exposed to synthetic seawater revealed that the rate of deterioration increases when the diameter of the samples decreases. |
| Nissa Mat Said et al., 2019 | Malaysia | Soft soil | A miniature model shows the percentage improvement in area and column height in modified soil under the design load. The results showed that the total decline decreased with the increase in the area and column height ratio. The particle image velocimetry (PIV) technique simulated the soil deformations without conducting large-scale tests. |
| Ni, Yi, and Liu, (2019). | China | Soft clay | Examine the composite ground's load capability beneath dams with varying stiffness levels. |
| Ni, Yi, and Liu, (2021). | China | Soft clay | Improving the loading capacity of the installed soil under soft fill, a T-shaped column, which works similarly as a platform for transferring loads, should be used. |
| Chen et al., 2021 | China | Soft clay | Developed a new methodology to study the performance of the stabilized layer with a foundation reinforced by a cement soil column, focusing on the transfer of loads to the stabilized layer. |
| Hasan and Canakci, 2022 | Iraq | Clayey soil | Constructing cement soil columns with injection at different pressures. The results showed that the strength decreased with the increase in the injection pressure, which indicates that the cement concentration decreased with increasing injection pressure. |
| Choudhary, Singh and Borana, 2023 | India | Clayey soil | Deep-cement mixing columns have gained popularity compared to other traditional soil improvement methods. |
| Zaika et al., 2023 | Indonesia | Clayey silt | Deep mixing can lower the danger of slope collapse and boost its stability by attaining internal and exterior stability by changing the cement content according to the moisture content or arranging cement columns that are very close to or overlap. |

## 4. Soil improvement techniques

Soil improvement means changing the properties of the soil to improve its engineering performance. The essence of land improvement is to enhance the engineering properties of weak soil to provide stability and sufficient bearing capacity for construction and other engineering purposes. There are many methods by which soil improvement is implemented on-site that increase shear strength and reduce compressibility. Soil stabilization is a general term used for any of the physical, chemical, or biological methods, or a combination thereof, that are used to improve soil properties. Improving the engineering properties of soil is imperative before erecting any structure on weak soils to prevent any futuristic engineering problems. Fine, expansive, collapsible, liquefied, soluble, dispersed, and silty sands with high organic matter are among the most dangerous types of soils that cause problems. These are found in different regions of the world and are susceptible to collapse potential when in contact with water[12][13].

Soil-improving techniques fall into two primary categories, which comprise the majority of approaches currently in use. Techniques like dewatering and compaction, which primarily deal with the soil without any additions, are included in the first level, whereas methods that rely on adding materials (chemical and physical) to the soil to improve it generally are included in the second tier[14].

Some of the techniques that are used to improve soft, cohesive soils in deep layers include dewatering (i.e., using vertical drains), mixes (i.e., using the deep mixing method), and reinforcing (i.e., using stone columns). Various deep compaction techniques are used for loose sandy soils, including dynamic and resonant compaction. Several methods are available to treat soft and loose soil at the surface layers, the most important of which is by strengthening and supporting the soil using lightweight synthetic materials[12]. Meanwhile, Mechanical compaction is the least expensive method. It can be applied to cohesive and cohesionless soils by removing the weak soil to the required depth, then refilling it or replacing it in layers with compaction. If the excavated soil is cohesive or a mixture of clay and sand, it can be suitably replaced in cohesionless soil layers and compacted. Meanwhile, using a heavyweight and repetitive, regular, high-energy dynamic compaction (DC) is another method of densifying soil. DC propagates pressure and shear waves that push soil particles into a denser state, transferring energy from the Earth's surface to deeper soil layers. The hammer is composed of concrete or steel and can be in a square or round shape, and the typical weights fall between 5 and 25 tons; dropping heights of up to 25 meters have been employed[12].

Vertical drains are a unique technology in which the drains are installed under additional load (preloading) to speed up the drainage of relatively impermeable soil and, thus, speed up the consolidated process. Drains provide a shorter path for water to flow away from the soil. Therefore, the time required to drain clay layers can be reduced from many years to a few months. Common types of vertical drains are sand drains and prefabricated vertical drains[15][16].

Soil improvement with admixtures and additives, considered as chemical treatment (cement, lime, fly ash, etc.), can also enhance the mechanical properties of soils, leading to the development of high-performance matrices.[17]. This category of soil improvement may also be known as in situ densification because it densifies the existing natural soil on the site. Stone columns and sand compaction piles are standard techniques used as an in-suite modification. Stone columns are frequently employed in cohesive soils to restrict the horizontal drainage routes of pore water flow, which increases shear strength, decreases excessive settlement, and speeds up consolidation. They are made by drilling holes that extend through the clay into more complicated soil. Then, compacted gravel is added to the hole. They can be installed as independent columns, continuous walls, or column panels. Their granular texture gives the surrounding soil more shear strength and they are superior to sand drains. When geosynthetic reinforcement is used, pressure is transferred from the soil to the stone columns because of the difference in stiffness between the two materials. This may prevent significant displacement and lessen total and differential settlement[18].

Chemical stabilization of soil can be accomplished by crushing natural soil, combining it with an additional chemical, and tightly compressing the mixture. To accomplish the intended impact, the native soil and the additive (such as lime, cement, fly ash, or a combination thereof) interact chemically. The main goals are to enhance soil performance, boost strength and durability, and lower soil compaction. Cement is the earliest binding agent since soil stabilization technology was developed in the 1960s, it is frequently used to stabilize various soil types. The soil becomes more complex to work with and crush as the percentage of clay increases, requiring more considerable cement additions to harden the soil. On-site, specialized machinery combines cement with water and soil, which involves many chemical and physical reactions. Applying cement will surround the soil like glue, but it will not change the soil structure. Soil hardening, such as cement soil[15][19]. Deep Mixing Columns method involves stabilizing the soil at a significant depth by injecting a wet or dry binder (lime or cement) into the ground and mixed with the clay soil on-site with a rotary or mechanical mixing tool for building a panel or column[20].

Researchers worldwide have begun using microorganisms to induce calcium carbonate precipitation from modern methods of soil improvement in recent years and from the principle of sustainable development to reduce chemical pollution. This biological ground improvement method has been successfully used to improve sandy soil. Also, unlike traditional methods, the electrokinetic method is a soil improvement technique without excavation. In this study (Karkush & Ali, 2023), MICP and electrokinetic techniques were used to improve the geotechnical properties of soft clay. is a soil treatment process based on the urease hydrolysis of bacteria containing the urease enzyme, resulting in calcite precipitation in the presence of dissolved calcium ions. The result was that the undrained shear strength ($C_u$) of the treated soil was higher than the soft clay concerning different concentrations, and the bearing capacity of the square footing increased with the increase of the molar concentration[21].

Using the magnetized water method to improve the properties of expansive soil, in a study by (AL-Ani et al., 2021), the effect of water magnetization on the properties of Atterberg limits, free swelling test, total dissolved salts, and unconfined compressive strength were evaluated. The inner surface of the soil container was coated with lubricating oil to reduce the effect of friction (interaction) between the soil and the container wall. After the soil layers were compacted to achieve the wet density, the soil container was placed in the water container. The water in this container was circulating in a magnetic field. Several types of water were used in this test (reverse osmosis and magnetized water under different magnetic intensities). Different magnetic field intensities greatly affect the main properties of swelling soil. The result was that the plastic properties (LL and PL) decreased significantly with increased magnetic field intensity from 500 to 2000 Gauss. However, the change of PI was slow, which reduced the possibility of soil swelling, and the unconfined compressive strength at the failure of the swelling soil increased with the increase of magnetic field intensity. The strength of the swelling soil was improved by reducing the possibility of such soil collapse and the hydromagnetic technology without using any chemicals or solution additives, and this new technology can be considered one of the sustainable solutions in geotechnical engineering[22].

## 5. Deep mixing column

Mixing column technology is used to improve the engineering properties of weak soils at great depths and is considered an essential economic method compared to other improvement methods. In addition, such methods work to reduce environmental pollution resulting from soil excavation operations and/or mixing soil with cement. Among the main objectives of using the mixing column technique in soil improvement are[15]:

- Increasing bearing capacity, shear, or friction force.
- Increasing density.
- Control deformation.
- Accelerates the consolidation process.
- Providing lateral stability.
- Control the seepage.
- Control the liquefaction.

Depending on the applications, the distribution occurs according to the following patterns shown in (Figure 1), Individual patterns, block patterns, panel patterns, or stable grid patterns[23],[24] Each of these designs is used in a variety of site settings based on the site's soil qualities, project needs, load transfer systems, and settling characteristics[20].

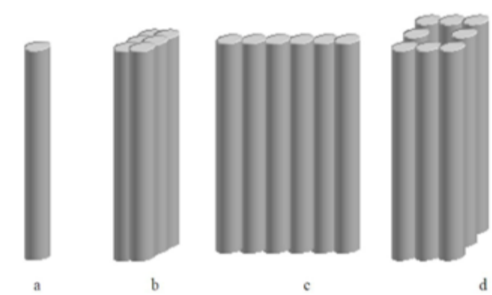


**Figure 1.** Variations in DSM column configuration: (a) Single column, (b) compound columns, (c) panels and (d) grid[24]

For instance, single columns are utilized in regions with modest design improvement ratios (less than 40 to 50%) between treated and untreated soil. When there is a significant design improvement on the site, "more than 50%"composite columns are utilized. Large-scale superstructures and high-ratio environments, such as embankments, dams, and retaining wall structures, also use panels and mesh. In highway applications, single or multiple columns are typically used to stabilize the soil[24]. The mixing columns may be of a single material or several composite materials. The pile system, which includes a soil cement column (SCC) and a spiral pile (SP), is an innovative alternative solution for foundations in soft, weak clay soils, such as Bangkok clay soil, as shown in (Figure 2). This technology has higher efficiency and productivity than substrates[25].

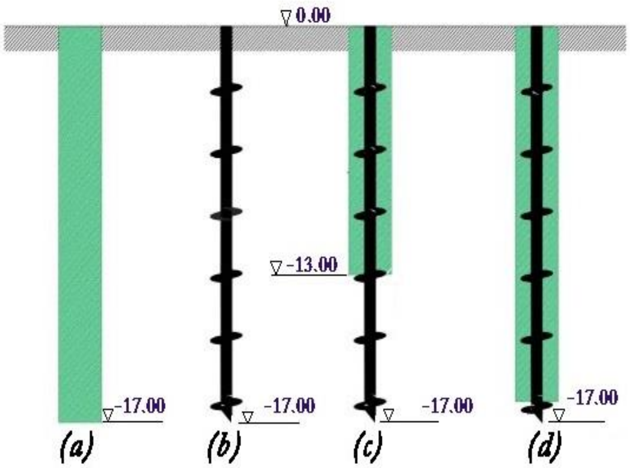


Figure 2. Types of studied pile: (a) SCC, (b) SP, (c) Partial SCSP, and (d) full SCSP[25]

The closely spaced soil cement columns in the classic deep mixing process indicate substantial space replacement ratios in construction projects. This kind of work has the potential to raise construction prices considerably. The high-replacement DM columns used in the range have been replaced by a new form of column devised and utilized instead: the T-shaped (TDM) column, as seen in (Figure 3).

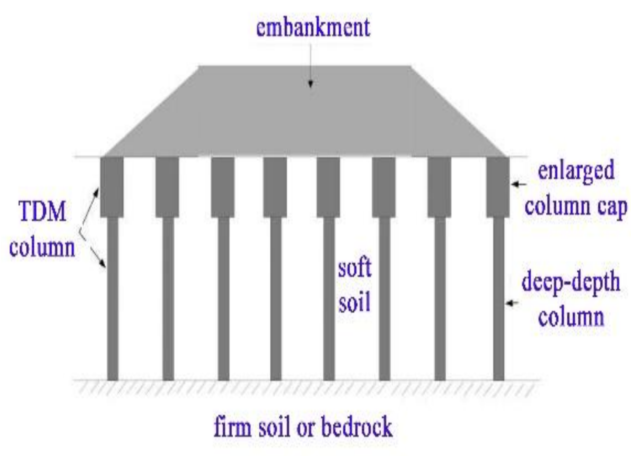


**Figure 3.** TDM column-supported embankment[26]

Unlike a traditional column, the new column's cross-section changes as it descends in installation depth. Large volumes of cement are injected and thoroughly mixed with the shallow soil using specifically made mixing blades[26]. Thus, treating soft soil and installing TDM columns on sites led to a cement saving of 15 and 7% by weight and a construction time saving of 28 and 19% compared to installing traditional DM columns[26].

## *5.1. Materials*

The deep mixing technique for stabilizing and improving the engineering properties of the soil has spread and gained great popularity worldwide. Materials used in installing these columns have developed and diversified. The most common method is mixing a binder that hardens, such as lime, cement, fly ash, or a mixture of these materials, with the soil. Lime comes in three different forms based on its chemical makeup. Less usually employed in soil stabilization are quicklime (calcium oxide; CaO) equation (1), hydrated lime (calcium hydroxide; Ca(OH2)) equation (2), and calcium carbonate (Ca(CO3) equation (3). These three chemical interaction species are listed below[27]:

$$CaO+H_2O \rightarrow Ca(OH)_2 + heat \quad (1)$$

$$Ca(OH)_2+CO_2 \rightarrow CaCO_3+H_2O \quad (2)$$

$$CaCO_3 + heat \rightarrow CaO+CO_2 \quad (3)$$

The availability of calcium, which aids in ion exchange during the pozzolanic reaction and depends on the reactive silicates and alumina present in the soil to be improved, is the most significant benefit of employing lime in the improvement process. Water reaction and the stabilizer itself are two sources of calcium hydroxide. (OH2)Ca) [27], It breaks down when combined with water, raising the pH and electrolysis of the soil in the process; dissociation of calcium hydroxide when mixed with water was mentioned (Schoute, 1999). With the following equation[28]:

$$Ca(OH)_2 = Ca^{+2} (2+) +2(OH)^\wedge(-) \quad (4)$$

By creating double layers scattered around soil particles, calcium ions produced during the dissociation of calcium hydroxide contribute to the cation exchange in the soil. When lime is combined with soil, this is the initial step of the chemical reaction.

Regarding the soil, the impact of these chemical reactions and exchanges will be felt in the soil's increased workability, decreased fluidity, and—above all—a minor increase in strength owing to the altered texture of the improved soil. calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) are the cement products that are formed in the second stage of reactions between the siliceous (Si) and alumina (Al) present in the clay on the one hand, and the calcium ions provided by the lime on the other. These processes, known as pozzolanic reactions, take place in highly alkaline environments and boost soil resilience as needed. These interactions can be represented by what (Nelson & Miller, 1997; Little, 1995) mentioned as the following[29][30]:

$$Ca^{2+} + 2(OH)^{-} + SiO_2 \rightarrow C\_S\_H(gel) \quad (5)$$

$$Ca^{2+} + 2(OH)^{-} + Al_2O_3 \rightarrow C\_A\_H(gel) \quad (6)$$

Aggregation and flocculation of soil particles ensue from the pozzolanic reaction, changing the texture of the soil and increasing soil resistance and plastic limits while decreasing the plasticity index, shrinkage stresses, compression, and permeability. The kind of soil and several of its characteristics influence how much lime is necessary for improvement. For instance, the pH and UCS values determine how much lime is required to amend soft clay soil[27].

Deep and shallow soil stabilization with cement has been used for many years. It has become a widely used technology due to its effectiveness in fortifying the soil and enhancing the performance of structures constructed on it. Complex chemical processes known as pozzolanic reactions improve soil resistance by making the soil more cohesive and decreasing volumetric changes by decreasing water absorption[27].

### *5.2. Type of deep mixing techniques*

The fundamental goal of these methods is to lessen the pressure on soft soil without appreciably altering the soil's structure. This is accomplished by laying down columns or piles in a bearing layer in a grid pattern. A load transfer mat made of geotextile reinforcement, also known as geogrid, is then frequently constructed over this. It is possible to raise the bearing capacity and shear strength of upgraded or composite ground while decreasing its compressibility. Since most column-type structures operate as vertical drains, the consolidation of soft soil can also be accelerated, significantly reducing post-construction settling. Tanks and warehouses are also constructed using vertical soil enhancement techniques. The deep mixing method improves soil at a great depth, where the treating material is injected, either wet or dry, into the earth and combined with the locally treated soil[23].

DM, or dry mixing, is the most popular technique because this process produces no damage that can be repaired, is silent and clean, and generates very little vibration. It has been used in Japan and northern Europe. This approach is done by injecting dry binders into the soil and thoroughly mixing with the wet soil using a specialized instrument; the soil is pre-mixed as it descends to the required depth. A dry binder is injected and combined with the pre-mixed substance as the mixing tool is removed. While this technique is known as Trevimix in Italy, it is also known as the Lime Cement Column (LCC) in Scandinavia and Sweden. A similar method is known as dry jet mixing (DJM) in Japan; in this method, a drilling motor and a mounting platform fixed to a track make up a standard DM machine. The powdered binder is fed via the mixing shaft by compressed air that passes through the hose. The rotating blade makes a hole filled with binder and air in the soil. This crushed material is combined with the original soil to harden the column inside the ground. This process can produce columns up to 1.5 meters in diameter and as deep as 40 meters. It should be noted that the method's effectiveness depends on the soil's moisture content. Therefore, the method is ineffective in sand layers with a low water content of less than 30%[23].

Early strength growth is achieved through the binding of soil particles by the cementitious gel (CSH) created during cement hydration[24].

*Advantages*[31]:

1. Easy to mobilize.
2. Low ground pressure under crawlers.
3. High installation capacity.
4. Cost-effective.
5. No or low spoil quantities.
6. Low noise and vibration levels.
7. No premixing required.

8. It can be performed in peat, gyttja, soft clay, silt, and sand.

*Disadvantages*[31]*:*

1.Limited to very soft and soft soils.

2.Introduces large quantities of air during installation.

3.Often requires a surcharge to consolidate the composite soil.

4.Causes heave and soil displacement during installation.

5.Lack of accurate quality control methods.

For a one-column machine, when necessary, a 'free blade', an extra blade about 100 mm longer than the diameter of the mixing blade (Figure 4), should be installed near one of the mixing blades to prevent apparent (limited rotation). The two twin-shaft machines revolve opposite directions, increasing mixing and enhancing machine stability. The mixing shaft is 267 mm in diameter and round in shape. The binding slurry is delivered to the mixing blades via a 50 mm-diameter pipe inserted in the mixing shaft.

**Figure 4.** Mixing blades and free blade for CDM method for on-land works[6]

As seen in (Figure 5), a set of blades, including a drilling blade and mixing blades, is fitted at the lower end of the mixing shaft. The solid metal tines are fixed to enable the machine to dig and stabilize the soil effectively, and the drill blade is installed at the end of the mixing shaft. Mixing blades cross one another at right angles at various levels. In order to prevent soil from obstructing the outlets, two bond mortar outlets are positioned on the columns at various levels close to the mixing blades(Figure 6), Intake injection is carried out through the upper outlet, whereas penetration injection is carried out through the lower outlet. To guarantee a mixing degree as high as feasible, the number and shape of mixing blades have been created, and there are now several variations depending on the Implementing company [6].

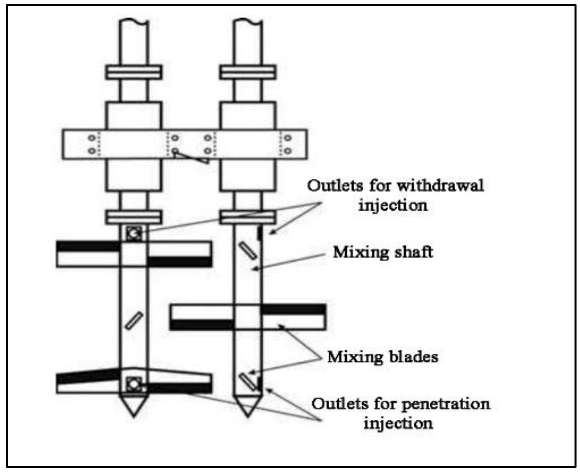


**Figure 5.** Typical mixing blades for on-land operations using the CDM method[6]

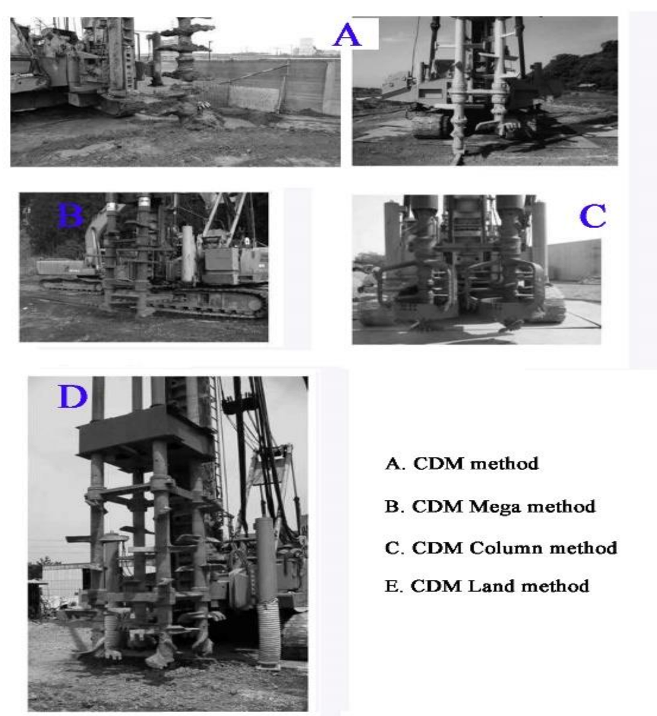


**Figure 6.** Several kinds of CDM method mixing shafts and blades (Photo is a courtesy of the Cement DMM Association)[6]

The wet deep mixing method involves a binder converted into a slurry, which is then injected into the soil through nozzles at the end of the auger. The mixing tool consists of a drilling rod and a fixed shaft on which cutting and scratching teeth are mounted on rotating chains and injection ports to deliver this material to the processing area. Depths of up to 45 m and widths between 0.5 m and 0.9 m can be achieved[6].

### *5.3. Engineering applications of DMC*

The practice of mixing soil is increasingly becoming a common method of treatment. Application regions, however, differ for various reasons, including soil type, strength, stability issues, subsidence, etc.; additionally, there are cost concerns, material and equipment availability, prior expertise, etc. Figure (7) shows examples of applying deep mixing for the different purposes [32]:

(1) Road Embankment: stable environment.

(2) Stability at high embankment.

(3) Uneven settling in the bridge abutment.

(4) The stability of the Cut Slope.

(5) Lessening the impact of adjacent construction.

(6) Braced Excavation: heaven and earth pressure.

(7) Foundation of the pile: lateral resistance.

(8) Sea wall: carrying capability.

(9) The bearing capacity of a breakwater.

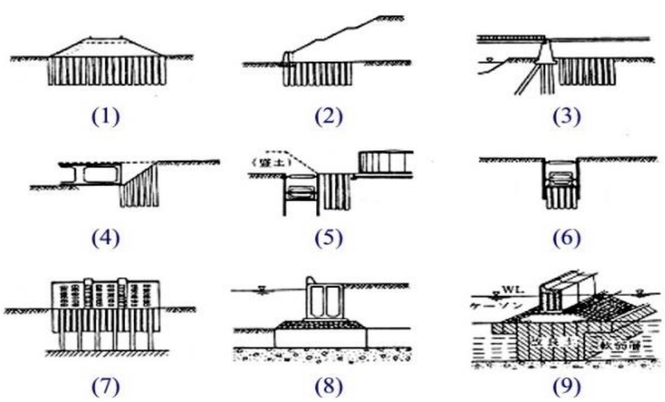


**Figure 7.** Deep mixing techniques and geotechnical design specifications in action[29]

Deep mixing applications also include foundation support systems for heavy machinery foundations, dams, highways, storage tanks, silos, and railway systems (Figure 8) for both shallow and deep foundations[18].

**Figure 8.** Foundation for Motorway Bridge near Katowice[18]


**Figure 9.** Top: TRD machinery in operation; Bottom: TRD wall inspection at Herbert Hoover Dike, which encircles Lake Okeechobee in southeast Florida[18]

Hydraulic barrier support systems, which install cut-off wall systems to prevent seepage and flooding, are one type of deep mixing application. Figure (9) illustrates how TRD was used at Herbert Hoover Dam in the United States of America to create a groundwater barrier[18]. It is also used for deep-mixing applications[18].

Retaining wall systems:

To keep the dirt behind it contained, DM can be used to construct a free-standing wall (Figure 10). Riverfronts, sea walls in ports and harbors, partition walls, water barriers, and open excavations can all benefit from these retaining walls, also known as gravity or reinforced wall systems[18].

**Figure 10.** Reinforced deep mixing retaining wall[18]

Excavation support systems:

In (Figure 11), applications include railway line trenches, buttressed excavations, building excavations, cutting and covering tunnels, and building support for open excavations. To keep open excavations, these can construct a retaining wall using deep mixing[18].

As seen in (Figures 12 and 13), deep mixing applications may include stabilizing dune deposits, mitigating lateral spreading, reducing liquefaction in river beds and riverbanks, reinforcing the area surrounding excavations and embankments, and seismic strengthening of the dam foundation. In this application, stabilization primarily aims to lower pore water pressures, raise liquefiable soil shear strength, and/or lessen wave propagation in superstructure and substructure systems[18].

**Figure 11.** Above A railroad trench excavating job for the Alameda corridor. Bottom: A structural cutoff wall built during the building of a new Harvard University building in Cambridge[18]

Earthquake and liquefaction mitigation systems:

**Figure 12.** Liquefaction mitigation along river bank at Napa Yatch club, California[18]

**Figure 13.** Application of DJM and resulting columns at Yodogawa River embankment in Japan(18)

## 6. Studies on deep mixing columns

### *6.1. Experimental studies:*

Presented (Zuo et al., 2023), a technique for controlling the cement concentration in deep soil mixing (DSM) columns is used in slope reinforcement to assess and maintain quality. A modified acetic acid with ethylenediamine tetra (EDTA) titration technique was used to determine the cement content of core samples. The study examined the impact of curing conditions and periods on the titration outcomes. The quality was assessed, and a link was developed between the unconfined compressive strength (UCS) and the cement content of DSM columns. DSM columns with various structural specifications[33]. The results showed that the failure strength of field cores in individual columns was between 15 and 55 percent lower than that of laboratory samples with the same cement content.

Provided (Wonglert et al., 2018) an explanation and analysis of how DCM's core length, hardness, and socket handle strength influence the behaviors of floating deep cement mixing (SDCM) shafts. Failure, landing mode, and final axial bearing capacity are among the observed phenomena. The study starts with a series of physical model experiments as an initial examination. Findings indicate that by inserting a reinforced core for the duration necessary to reach the maximum load capacity, DCM handle strength may be lowered to a particular value. This shows the ideal length of the reinforced core for a particular DCM handle strength[34].

Conducted (Hashim & Islam 2008) a field model study to examine the effects of various binders and a deep mixing technique on engineering qualities to stabilize peat soil. A few cement soil model columns were built on the spot, and the mechanical characteristics of stabilized peat soil, including its undrained shear strength, unconfined compressive strength, and shear strength during a 14-day curing period, were measured. Energy dispersive X-ray (EDX) testing and scanning electron microscopy (SEM) were also carried out to examine the stabilized peat soil microstructure. The test findings demonstrated that additives can enhance the stabilized peat soil's engineering qualities[35].

(Pongsivasathit et al., 2017) studied the adhesion behavior of fine clay deposits enhanced by a cement slab fixed to the ground surface and a floating soil column by evaluating the laboratory model with finite element analysis and a symmetric unit cell model. Assess the impact of the slab's thickness and undrained shear strength on the column's relative penetration into the surrounding soil. Based on the findings, the proposed approach was adjusted to compute the subsidence of a floating column in the enhanced soft subsurface. In other words, figure out how deep the soil layer is at the base of the column's enhanced region[36].

Presented (Duan, 2021) a technique for estimating pile ultimate capacity using the pile static load test's load-to-settlement curve. The results indicated a small amount of strain close to the pile tip. The pile's principal deformation spans from 0 to the effective length (lc), beyond which the strain in the pile is less than 10%. The load increase mostly impacted the pile deformation range from 0 to lc and only slightly above lc[37].

A study by (Ahmed and Wilshtwan, 2021) for two different soil: sandy and clay. Unconfined compressive strength data were collected by analyzing several research on the efficacy of deep soil mixing and soil stabilization techniques as ground improvements utilizing cement as an additive throughout a 28-day curing period. The most effective approach to achieve high durability was determined by analyzing the durability of cement content in the range of 8% and 10% or more, based on the findings of the unconfined test of clay soil. The unconfined compression test findings showed that as the cement content increased throughout the 28-day curing period, so did the strength of the employed soil. Cement is applied at 4%–8% on sandy soil. It has been found that employing cement with a content of more than 4% results in high strength, improving the soil's softness and suitability for use in any project. These findings indicate that adding 4% or 8% of sand to deep soil improves it to a higher degree of efficiency. Furthermore, compared to clay soil, sandy soil yields more significant strength gains. Additionally, it took more than 8% or 10% to enhance clay soil, indicating the need for several aspects, such as the differences in the physical characteristics of clay and sandy soil[38].

Showed (Tanseng, 2012) how to create and erect a soil-cement column (SCC) wall that can be used as a retaining wall while excavation is underway. SCC wall supports are used instead of traditional supports to lessen ground movement. The lateral ground motions behind a buttressed diaphragm wall are comparable to those behind an SCC wall. By contrasting the SCC wall stud's performance in this study with case history data, the following conclusions were drawn[39]:

- An unreinforced SCC wall can function well as a retaining wall without other supports, decreasing construction time and expense. During excavation, the existing structure was not damaged.
- The instruments show comparatively little lateral movement, unlike a typical plate pile and wall,
- When comparing SCC walls with and without bracing, the ground movement caused by the bracing can be minimized.

Reported (Kazemian et al., 2012) the shear strength data in their research. Cement was applied to peat in varying amounts to produce columns. They used a dry mixing method to stabilize the columns of a laboratory model consisting of fibrous, hemi- and capric peat. The samples were cured for 28 days to evaluate the shear strength parameters and then subjected to triaxial testing. The results showed that adding soil columns could significantly increase the shear strength of peat and stabilized cementitious materials. They found that the stress-strain graph of reinforced peat was affected by the column diameter and the amount of cement used in its construction. Moreover, the results showed that cement had a greater effect on capric peat due to its chemical and physical properties[40].

### *6.2.Numerical studies*

Because of the limitations of the finite element software PLAXIS 3D in modeling expansive soil behavior, numerical simulation experiments conducted with the program did not produce adequate findings. On the other hand, in the ultimate stress level, or 100% saturation, the treated ground behaved as expected. Understanding the interaction mechanism between DSM columns, the untreated soil surrounding the columns, and the geogrid anchored on the columns becomes necessary as a result, necessitating "future research"[24].

East Port Said Port, characterized by soft clay soil, is one of Egypt's most important industrial sites. (Zakaria et al., 2020) Improve the soil using the deep mixing method (DMM), quicklime, or ordinary Portland cement. The soil properties before and after treatment were compared in the laboratory using experimental mixing designs. In addition, they investigated the effect of different water-to-cement ratios, binder types, binder contents, and curing times on the improvement of acceptable clay. A software called PLAXIS 2D was used to conduct finite element analysis; comparison of the physical model's output and the 2D finite element analysis results showed that the effects of depth, spacing, diameter, type of column, and soil pressure index, and they are typically consistent[41].

provided (Chai et al., 2009) an altered approach to forecasting the lateral soil displacements brought about by installing cement soil columns. This approach combines the original technique, which was developed using the theory of growing cylindrical cavities in an infinite medium, with the addition of a correction function to account for the columns' finite length. For a single-column installation, correction functions have been established by comparing solutions derived using the spherical and cylindrical cavity expansion theories[42].

(Ahmed et al., 2015). They conducted a series of physical model experiments were conducted using fully and partially penetrated cement columns that were unreinforced in order to compare the failure behavior of the deep mixing (DM) method under rigid and flexible foundation models. Particle image velocimetry (PIV) and near-field photogrammetry were used to measure the failure process. The bearing capacity value derived from the experiment and the numerical program agreed well, as demonstrated by comparing the bearing capacity performance and failure mechanisms with the numerical analysis of the ultimate limit state[19].

To simulate the behavior of injection columns, (Sedighi et al., 2017) performed several numerical calculations using the finite element method and an advanced constitutive model. The results indicated that the improved soil caused a decrease or increase in the seismic load. Moreover, it was shown that potential fracture zones in cement columns could be identified using an advanced model[43].

In order to improve soft soil, in a study by (Ni et al., 2019), cement soil columns were used repeatedly, and the crucial design parameter is the composite ground's bearing capability. Based on a computational model that can capture the strain-softening behavior of cement soil columns, a design technique was created to compare the bearing capacity behavior of floors installed beneath solid bases and under-fill embankments. The findings show that the kind of backfill influences the failure mode. Ground with soft clay and dredged slurry, soil failure happens before column failure, but with embankment backfill, column failure is the primary mode of failure for composite floors. Soil arching hypotheses can explain this variation in the composite floor failure manner[44].

To assess the stability of the channel slope, [45] they ran several finite element method (FEM) simulations in PLAXIS 2D under various circumstances, including varying water levels. Additionally, study how a column's strength is affected by elements like the amount of cement used and the surrounding environment, which includes the air, soil, freshwater, and saltwater. The findings demonstrated that CDM columns with a diameter of 0.5 meters were employed to increase the stability of the slope of the Chu Gao Canal in Vietnam. These columns were placed in three rows at a distance of 0.5 meters, and each column was intended to be 10 meters long[45].

## 7. Advantages of deep mixing columns

The advantages of deep mixing technology include its relatively low cost per unit volume for depths up to 40 m and its high production capacity in certain conditions (up to 200 m2 per shift). Performance can be checked quickly on site, which is why it is economical on large projects and sites where the soil type is very soft and compressible. It can be used in marine projects and most soils and backfills (without obstructions). Dry mix methods also provide meager amounts of damage, and the waste material generated by wet mix methods is an excellent site-fill material characterized by stability, straightforward implementation, and relative flexibility. In design, it varies depending on the diameter and spacing of columns or the thickness of the panels, and the spacing and configuration of individual columns are infinitely variable. An important thing about this technology is that it can control noise (it can mute the sound of equipment) and low vibrations to prevent affecting neighboring buildings. The strength of the treated soil ranges from 0.5 to 4 MPa, and the lateral and lateral vertical processing is generally good and can treat heterogeneous layered soils. Organization, and because the permeability is relatively low, there is no need for additional insulators.

However, this method has caveats and drawbacks, such as it requires ample working space for large, powerful equipment and no general restrictions. The weight of the equipment may pose a problem for fragile soil, and it cannot be installed close to existing structures. Underground facilities may cause problems and do not apply to soil very dense, hard, or may contain rocks. There may be significant variation in the treated soil's strength, which may be necessary in some applications. There is limited ability to install it except vertically[46].

## 8. Conclusion

As well known, silty soils can be classified as problematic and cause many structural engineering problems. Therefore, its engineering characteristics should be enhanced to satisfy the requirements for use in civil engineering applications. The published papers displayed that the cement column or deep cement mixing technique could contribute to better strength and lesser settlement of weak soils. Hence, from the above review collected from various locations, the following conclusions can be drawn:

-Cement columns were developed to increase the strength and reduce the settlement of weak soils. It is also a good soil enhancement technique that increases the bearing capacity of soils under lateral loading conditions.

-Generally, increasing the diameter and the length of the cement column leads to more enhancement areas surrounding the column due to more chemical ions traveling to that area.

The pozzolanic reactions occur mainly in cement and carbonation materials. As a result of these reactions, the ground temperature increases. The decrease in the moisture content in the soil leads to an increase in shear resistance and a decrease in the soil's compressibility, which encourages the choice of the column technique containing cementitious compounds more than other soil improvement methods.

- Most soil improvement methods involve various activities that lead to environmental and economic impacts. The largest impacts (especially cost and duration) are usually considered when choosing the appropriate technique. However, potential large impacts such as carbon dioxide emissions and consumption of raw materials can be noted. Several indicators will be taken into account to reduce environmental and economic impacts, which include[44]:

1) Using an environmentally friendly material to improve soft soil instead of other alternative techniques.

2) Improving deep soft soil contributes to sustainable development instead of using deep foundations to reduce environmental and economic impacts.

3) Using low-energy materials leads to reducing carbon emissions.

4) Using a contaminated site instead of abandoning it and using an alternative site.

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