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# Soil Improvement Techniques

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**Abstract**— Soil at a construction site may not always be totally suitable for supporting structures in its natural state. In such a case, the soil needs to be improved to increase its bearing capacity and decrease the expected settlement. This paper gives an overview of techniques that are commonly used to improve the performance of saturated clayey soil in situ, its functions, methods of installation, the applicable soil types and cost of those techniques. Then, this study concluded that there is an urgent need to study the technique of removal and replacement for improving soil behavior taking into consideration geotechnical requirements (i.e. bearing capacity and settlement) and cost to achieve the optimum thickness of replacement layers and the most suitable material corresponding to minimum total cost of foundation works.

**Index Terms**— soil improvement, soil replacement, preloading, drains, stone column, chemical stabilization, jet grouting, thermal methods of soil improvement.

## 1. Introduction

Existence of unsuitable soil for supporting structures in construction sites, lack of space and economic motivation are primary main reasons for using soil improvement techniques with poor subgrade soil conditions rather than deep foundation. Several methods are commonly used to reduce the post construction settlement ,enhance the shear strength of the soil system , increase the bearing capacity of the soil, and improve the stability of dams and embankments [1] [2]

Chu [3] stated that soil improvement techniques can be divided into four main categories:

- Soil improvement without admixtures (soil replacement, preloading, sand drains, vertical drains,…)
- Soil improvement with admixtures or inclusions (stone columns, sand compaction piles,…)
- Soil improvement using stabilization with additives and grouting methods (chemical stabilization, Deep mixing, jet grouting,…)
- soil improvement using thermal methods (Heating , Freezing)

Many researches have been done to study the different methods of soil improvement. Some of these researches focused on increasing soil bearing capacity and / or decreasing the expected soil settlement. On the other hand, another point of view was how to minimize construction costs when improving soil. But there is a lack of researches which consider all the governing factors such as soil bearing capacity and settlement, cost of foundation works and simple execution.

## 2. Soil Improvement Without Admixtures

This category of soil improvement is widely and commonly used. It can be executed using many techniques including removal and replacement, pre compression, vertical drains and soil reinforcement.

### 2.1. Soil Replacement

Soil replacement is one of the oldest and simplest methods which improve the bearing soil conditions. The foundation condition can be improved by replacing poor soil (eg. organic soils and medium or soft clay) with more competent materials such as sand, gravel or crushed stone as well, nearly any soil can be used in fills. However, some soils are more difficult to compact than others when used as a replacement layer. [4]

The use of replacement soil under shallow foundation can reduce consolidation settlement and increase soil bearing capacity. It has some advantages over other techniques and deep foundation as it is more economical and requires less delay to construction. Despite of soil replacement's advantages, the determination of the replacement soil thickness is based on experience which in many cases is questionable [5]. P.C.Varghese [6] stated that the region of high stress in a shallow foundation is only 1 to 1.5 its breadth and this part can be replaced by selected good soil.

Abdel Salam [4] and Abdel Fatah [7] investigated the effect of using different types and thickness of replacement layer on increasing bearing capacity and reducing consolidation settlement of soft clayey soil experimentally and concluded that, with increasing replacement layer thickness the vertical settlement decreased.

### 2.2. Pre Compression or Preloading

Pre compression or preloading technique is simply to place a surcharge fill on the top of the soil that requires large consolidation settlement to take place before construction of the structure. Once sufficient consolidation has occurred, the fill can be removed and construction process takes place. In general, this technique is adequate and most

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effective in clayey soil. Since clayey soils have low permeability, the desired consolidation takes very long time to occur, even with very high surcharge load. Therefore with tight construction schedules, preloading may not be a feasible solution. Hence, sand or vertical drains may be used to accelerate consolidation process by reducing the drainage paths length. [8] [9]

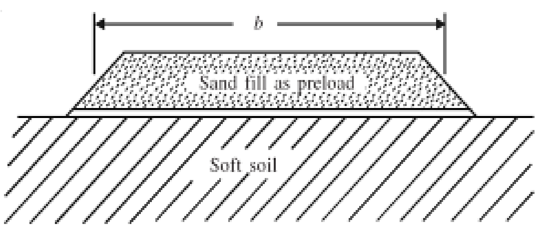


Fig. 1. Soil improvement by preloading (after, P.C.Varghese 2005)

## 2.3. VERTICAL DRAINS

Vertical drains is a unique technique in which the drains are installed under a surcharge load to accelerate the drainage of relatively impervious soils and thus speed up consolidation. The drains provide a shorter path for the water to flow through to get away from the soil. So, time to drain clay layers can be reduced from many years to a few months. The common types of vertical drains are sand drains and prefabricated vertical drains.

### 2.3.1. SAND DRAINS

Sand drains are constructed by drilling holes through the clay layer by using rotary drilling, continuous flight auger or driving down hollow mandrels into the soil. The holes are then filled with sand.When a surcharge is applied at the ground surface, the pore water pressure in the clay will increase, and it will be dissipated by drainage in both vertical and horizontal directions. Hence the settlement is accelerated [2]

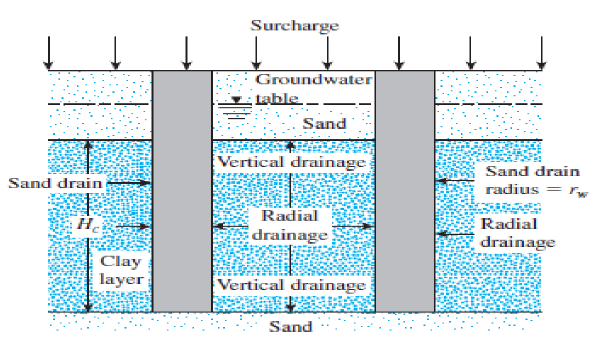


Fig. 2. Sand drains (after, Das 1983)

Sand drains can work as sand piles. They reinforce soft soil in which they are installed. Even though sand drains replace only 1 to 2% of soil volume, the overall improvement in bearing capacity may be more than 10 % [6]

But on the other hand, they have some disadvantages:

- Installation of sand drains by driving down hollow mandrels causes a disturbance of the soil surrounding each drain. This may reduce the flow of water to the drain.
- During filling, bulking of the sand might appear which could lead to cavities.
- Construction problems and/or budget problems might arise due to the large diameter of sand drains. [8] [10]

### 2.3.2. PREFABRICATED VERTICAL DRAINS (PVDS)

Prefabricated vertical drains also known as wick drains consist of channeled synthetics core wrapped in geotextile fabric as shown in figure (3). They are flexible, durable, inexpensive and have an advantage over sand drains is that they don't need drilling. [11]

PVD is best suited in clay, silt, organic layers, clayey and silty sand. PVD is placed into steel mandrill then the mandrill is pushed into the ground to the determination depth with a mast mounted on back hoe. Anchor plate is attached to the wick material to hold it in place as mandrill is removed. Then the PVD is cut off a little above the ground. [12]

PVDs are used to reduce surcharging process time and accelerate settlement not reduce it. Pore water will move laterally to the nearest drain instead of moving vertically to the permeable layer. Therefore, the drainage distance decreased. Whenever the distance between drains becomes closer, the surcharging time decreases [12]

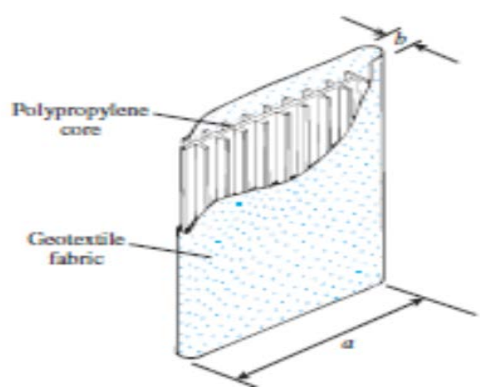


Fig. 3. Prefabricated Vertical Drains (after, Das 1983)

## 3. Soil improvement with admixtures or inclusions

This category of soil improvement may also be known as "in-situ densification" because it results in densing the

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natural soil existing in the construction site. Stone columns and sand compaction piles are two of the common techniques used in this way

### 3.1. Stone columns

Stone columns are popularly used in cohesive soils to improve shear strength, to reduce the excessive settlement and to speed up the consolidation by shortening horizontal drainage paths for pore-water flow [13].

As shown in figure (4), Stone columns are constructed by drilling holes that extend through clay to firmer soil. Then the hole is filled with compacted gravel [2]. They can be installed as either independent columns or as continuous walls or panels of columns [1].

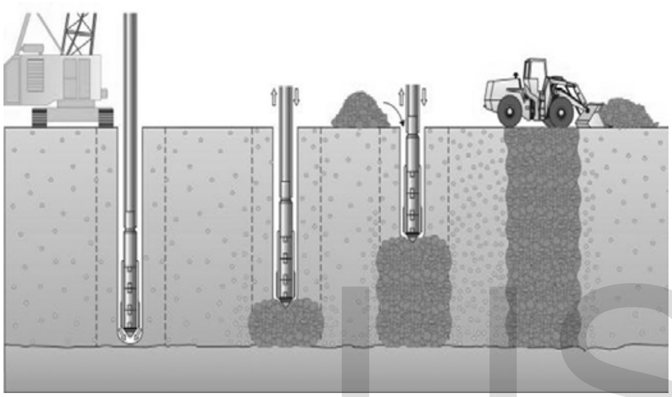

Fig. 4. Installation process of stone column (after, Hussein 2006)

Stone columns are more preferable than sand drains because of its granular nature which provide additional shear strength to the surrounding soils. They reduce settlements by promoting soil arching which transfers the loads from the surrounding soil to the stiffer columns. [1]After [14]

The geosynthetic-reinforced fill and stone column system can provide an economic and effective solution for structures constructed on clay soil. The use of geosynthetic reinforcement transfers the stress from soil to stone columns due to stiffness difference between the stone columns and soil, and this may prevent large displacement and reduce the total as well as differential settlement. [15]

## 4. Soil improvement using stabilization with additives and grouting methods.

Soil stabilization method is widely used to improve soil strength and decrease its compressibility through bonding the soil particles together. Additives or grout are mixed with soil to bring about the stabilizing action required.

### 4.1. Chemical Stabilization

Soil stabilization can be achieved by pulverizing the natural soil, mixing in a chemical additive, and thoroughly compacting the mixture. Under this category, soil stabilization depends mainly on chemical reactions between the additive (such as lime, cement, fly ash or combinations of them) and the natural soil to achieve the desired effect [16]. The main purposes of stabilizing soil are to improve the performance of the soil, accelerate settlement, increase the strength, the durability and reduce the compressibility of the soil [17].

#### 4.1.1. Cement stabilization

Cement is the oldest binding agent since the invention of soil stabilization technology in 1960's. It is commonly used to stabilize wide range of soils, provided sufficient quantity is added. As clay content increase, soils become more difficult to pulverize and work, and larger quantities of cement must be added to harden them. Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil. This can be the reason why cement is used to stabilize a wide range of soils. [16]

In this technique, cement is mixed with water and soils by special equipment in site. Physical and chemical reactions within cement and soil are happened. Setting of cement will enclose soil as glue, but it will not change the structure of soil. The soil is hardened as cemented soil. Hardening process can be affected by physical and chemical properties of soil, water-cement ratio, curing temperature and the degree of compaction. [18]

On the other hand, the nature of soil treated, the type of cement utilized, the placement and cure conditions adopted affect determining the correct proportion of soil - cement [19]

#### 4.1.2. Lime stabilization

Lime provides an economical way of clayey soil stabilization. Selection of the suitable lime concentration for clay stabilization is based on achieving a target pH value. Stabilization can be ineffective if the concentration of admixture is not adequate to ensure strength and durability.it is usually in the range from 5 to 10% [17] [2]. Lime can be mixed with the soil either in plant or in site or lime slurry can be injected in to the soil [2]

The improvements in soil properties are attributed to the soil-lime reactions (cation exchange and flocculation – agglomeration). In these reactions, monovalent cations associated with clay are generally replaced by divalent ions. flocculation – agglomeration produces changes in clay texture and clay particles become larger there by improving soil strength. [20]

#### 4.1.3. Fly-Ash stabilization

Stabilization of soils with coal fly ash is an increasingly popular alternative nowadays. Fly ash is a product of coal fired electric power generation facilities; it has little cementitious properties compared to lime and cement.

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Most of the fly ashes belong to secondary binders; these binders cannot produce the desired effect on their own. [16]. Therefore, the use of fly ash to stabilize clay must usually be in concert with lime or cement. For example" type F" fly ash is ineffective as stabilizer without the addition of lime as a source of calcium. [21]

Fly-Ash and cement have significant environmental impacts associated with its production in terms of high energy consumption and CO2 emissions. [22]

### 4.2. Deep mixed columns

The deep mixing method involves the stabilization of soils at large depth. It is an in situ ground modification technology in which a wet or dry binder (lime or cement) is injected into the ground and blended with in situ clayey soils by mechanical or rotary mixing tool to create a column, or panel of columns.

Deep mixed columns are similar to stone columns. They reduce expected settlement by promoting soil arching which transfers the loads to stiffer panels rather than insitu soil. But the main difference between them is that strength of stone columns is dependent on the friction angle of the aggregate and confinement from surrounding soils; while deep mixed columns have internal strength from cohesion. Deep mixed columns are constructed such that they are continuous panels and the groundwater flow will be reduced. [23]

### 4.3. Jet Grouting

Jet grouting proves its effectiveness across wide range of soils. It is an erosion-based system. Granular soils are considered the most erodible and plastic clays the least. The technique hydraulically mixes soil with grout to create in situ geometries of soilcrete. [11]

Hydraulic Rotary drill is used to reach the design depth and at that point grout and sometimes water and air are pumped to the drill rig. This create a cementitious soil matrix called soilcrete [24]

As shown in figure (5), there are three traditional jet grout systems:

- The single-fluid system

a high-velocity cement slurry grout is used to erode and mix the soil. This system is most effective in cohesion less soil

- The double-fluid system

The high-velocity cement slurry jet is surrounded with an air jet. The shroud of air increases the erosion efficiency. The double-fluid system is more effective in cohesive soils than the single-fluid system.

- The triple-fluid system

A high-velocity water jet surrounded by an air jet is used to erode the soil. A lower jet injects the cement slurry at a reduced pressure. Separating the erosion process from the grouting process results in higher quality soilcrete and is the most effective system in cohesive soils [11] [24]

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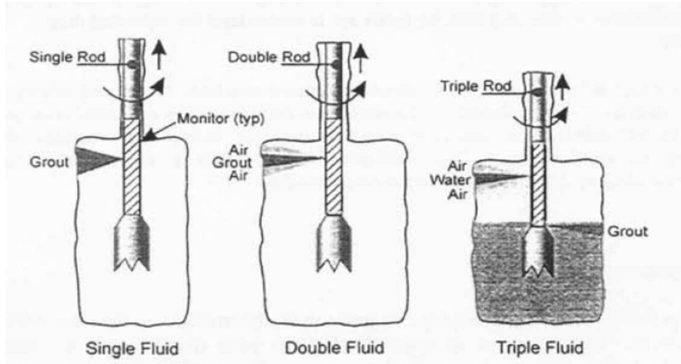


Fig. 5. Jet grouting system (after, burke 2004)

## 5. Soil improvement using thermal methods

Heating or freezing a soil can cause marked changes in its properties. Although thermal stabilizations appear to be very effective, the use of these methods is limited because of its high cost.

### 5.1. Soil Heating

Raj [19] Stated that the higher the heat input per mass of soil being treated, the greater the effect. Even small increase in temperature may cause strength increase in fine grained soils by reducing the electric repulsion between the particles, a flow of pore water due to thermal gradient and a reduction in moisture content because of increasing evaporation rate. Table (1) shows the effect of increasing the temperature on changing soil properties.

TABLE 1

THE EFFECT OF TEMPERATURE INCREASE ON THE PROPERTIES OF CLAYEY SOIL

| Temperature | The effect |
|---|---|
| 1000 C | Can cause drying and significant increase in clay strength |
| 5000 C | Can cause permanent changes in the structure of clays hence decreasing its plasticity |
| 10000 C | Can cause fusion of clay particles into a solid substance |

Heating is applied to the soil by burning liquid or gas fuels in boreholes or injection of hot air into 0.15 to 0.2 m diameter boreholes that can preduce 1.3 to 2.5 m diameter stabilized zone after continous treatment for about 10 days.

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This techniques can be effectively used when a large and inexpensive heat source is located near the site. [19]

### 5.2. Soil Freezing

Soil freezing involves lowering the temperature of the soil until the moisture in the pore spaces freezes. Freezing of pore water acts as a cementing agent between the soil particles causing significant increase in shear strength and permeability [25].

Unlike soil heating, soil freezing may be applicable to a wide range of soil types, grain sizes and ground conditions. Fundamentally, the only requirement is that the ground has sufficient soil moisture (pore water) [26].

The process typically involves installing double walled pipes in the soil. A coolant is circulated through a closed circuit. A refrigeration plant is used to maintain the coolant's temperature [11].

## 6. Cost of soil improvement techniques

Most of researches investigated the effect of using different soil improvement techniques on increasing soil bearing capacity and /or decreasing the expected settlement while, a few researches considered the cost of foundation works as one of the governing factors when selecting between different soil improvement techniques.

A case study of a silo 23,000 ton alumina, 30 m in diameter and 35 m in height was constructed on a deposit of medium sand to a depth of 18 m then underlain by stiff clay from 18 to 35m.different improvement techniques are reviewed based on cost ratios and expected settlement in table (2).

TABLE (2)

COST RATIOS AND EXPECTED SETTLEMENT FOR DIFFERENT SOIL IMPROVEMENT TECHNIQUES (AFTER, P.C.VARGHESE 2005)

| Method | Cost ratios | Expected settlement (m) |
|---|---|---|
| Pre loading (taken as base) | 1.0 | 0.2 |
| Sand Compaction piles 18 m | 12.0 | 0.25 |
| Stone columns to 18 m | 15.0 | 0.25 |
| Concrete piles to 17 m | 26.0 | 0.25 |
| Concrete piles to 35 m | 60.0 | 0.08 |

The cost ratios for another case study of oil tank constructed on 27 m soft clay are discussed in table (3):

TABLE (3)

COST RATIOS FOR DIFFERENT SOIL IMPROVEMENT TECHNIQUES AFTER [6]

| Method | Cost ratios |
|---|---|
| Preloading without drains | 1.0 |
| Preloading with 28 m deep sand drains | 3.0 |
| Piles to a depth of 30 m | 20.0 |

## 7. Conclusion

There are many available improvement techniques that can be used for the purposes of increasing bearing capacity, enhancing shear strength and decreasing consolidation settlement of saturated medium clay such as soil replacement, preloading with vertical drains, stone columns, stabilization with additives and thermal methods. Unfortunately, there is a lack of researches which consider all the governing factors such as soil bearing capacity and settlement, cost of foundation works and simple execution. This paper concluded that there is an essential need to study the technique of removal and replacement for improving soil behavior taking into consideration geotechnical requirements and cost to achieve the optimum replacement layer thickness and the most suitable material corresponding to minimum total cost of foundation works.

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