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Reviewing the most suitable Soil Improvement Techniques for treating soft clay soil

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ABSTRACT—The first query comes to mind when planning to construct a building is: Will the soil totally be suitable for carrying the building? This question makes engineers and researchers do all the required tests and investigations, for example bearing capacity and settlement..etc, to get the perfect answer. The desirable answer is: the soil is perfectly suitable to support the building. If it is not, soil improvement will be required before constructing the building. Many soil improvement techniques could be applied to increase its bearing capacity and decrease the consolidation settlement. This paper will be focused on overviewing some techniques that improve soft clayey soil, idea about the techniques, how they are applied, and their functions. Despite all the soil improvement techniques, soil could still not suitable to support the building taking in considerations the bearing capacity and the settlement. Soil removal and replacement will take place in such a case. The maximum depth of removing and the best material to replace the weak soil will be discussed as well.
Keywords—Soft clay, Settlement, Shear Strength, Compaction, Stone columns.

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I. INTRODUCTION

What does make us deal with problematic soils and try to improve their properties instead of using deep foundation to reach strong deposit? This question has obvious answer. Firstly, improving the soil is much cheaper than using deep foundation instead. Second, not enough space could oblige us to improve the properties of soil rather than using piles. Das 1983 classified the soil improvement techniques to many general methods. For example, shallow compaction, preloading, sand drains, vibroflotation, admixtures stabilization, deep mixing, stone columns, sand columns, jet grouting, and deep compaction by using compaction piles. These techniques were more detailed by Kempfert and Gebresealssie 2006 . The main classification was into three main techniques, consolidation, soil replacement, and using columns. Each of these techniques were classified into many methods in details as shown in figure 1.

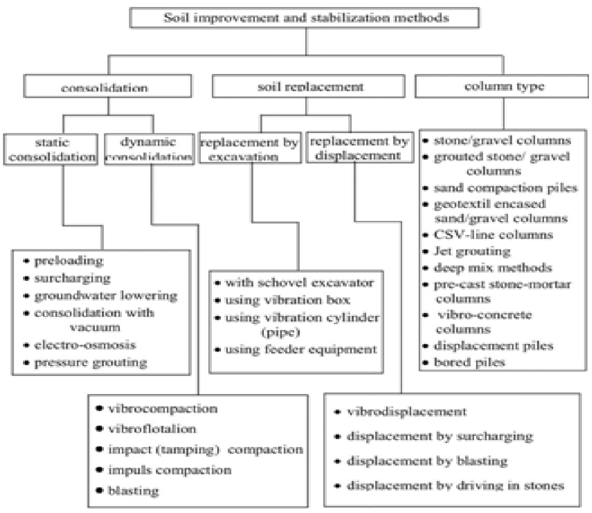

FIGURE 1 SOIL IMPROVEMENT TECHNIQUES CLASSIFICATION (AFTER KEMPFERT AND GEBRESEALSSIE 2006)

This study will discuss some of the soil improvement techniques to increase the bearing capacity and reduce the expected settlement of soft soil.

II. SOFT CLAYEY SOIL IMPROVEMENT TECHNIQUES

2.1 Soil improvement technique without admixtures

This technique is widely used all over the world and it could be classified into three major techniques will be discussed in this paper. These three techniques are soil removal and replacement, preloading technique, and finally the vertical drains.

2.1.1 Soil removal and replacement

This technique is desirable to be used instead of using deep foundations in case of existing a thick deposit of soft clay soil. The reason behind that is that the soil replacement is much cheaper and easier to apply than the deep foundations. A. K. Gabr 2012 replaced the top layer of soil which was soft clay by graved or dense sand with keeping the shallow foundation to support the building rather than using piles. The issue was treated numerically Mohr-Coulomb soil behavior model and experimentally using centrifuge modeling and the study results exhibit reducing the settlement and the construction cost. The only disadvantage of using this technique is that; there is no clear technique to estimate the replacement thick and it totally depends on the experience [5].

On the other hand, Mohammed Y. Fattah, studied the effect of partial replacement on the bearing capacity and shear strength of soft soil. He came up with important two points. Firstly, the partial replacement of soil with granular soil exhibits maximum effect in case of using trench pattern. The trench pattern has dimensions of B, which is equal to the foundation width, with Stretching the width B/2 each side and 1.5B for depth. Second of all, increasing the width of replacement is more effective than increasing the replacement depth in improving the bearing capacity.

2.1.2 preloading or pre-compression technique

When a soft clayey soil with high compressibility potential is existed at a limited depth from the ground, preloading and pre-compression technique is highly recommended, especially when the soil supporting high weight building, highway embankment, earth dams Das 1983. Preloading the soil would definitely decrease the expected preconstruction settlement. Preloading techniques could be done using sand, gravel and water or oil tanks [4]. Another way could be used as a preloading technique by lowering the water table. Pre-compression technique is highly effective in minimizing the settlement that expected to happen in after construction the building. Moreover, it increases the shear strength and bearing capacity of soil as the density increase and void ratio decreases [4]. This technique is more effective for normally or lightly over-consolidation soils and it makes the consolidation settlement process completed in eight months at most. The height of the fill material is about eight m and that cause a settlement of about 1 meter at most depending on the soil and the type of surcharge, [2].

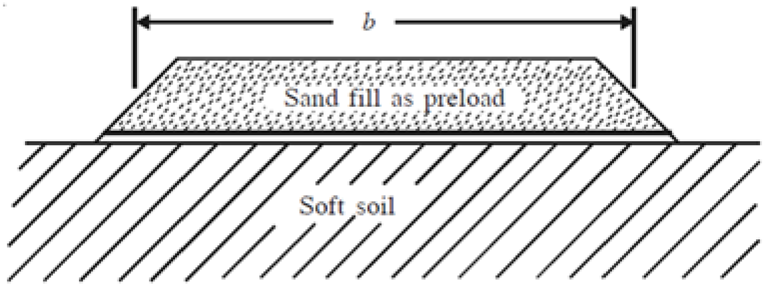

Figure 2 preloading soil improvement technique (After, P.C.Varghese 2005)

2.1.3 Vertical Drains

When the soil preloading is set on the soft soil, has low permeability, the path length of drainage will be increased. This issue might increase the time required for water to run away from the subsoil under the fill or preloading and it should be as less as possible. For that reason, vertical drains are necessary in this situation which reduce the length of the drainage path. These vertical drains speed up the water to flow out the subsoil construction area which reduces the consolidation time from many years to few months [4]. Two major vertical drains techniques will be discussed in this paper, sand and wick drains.

2.1.3.1 Sand Drains

Sand drains is one of the vertical drains to accelerate the consolidation settlement of soil, soft clay and normally or lightly over-consolidated clayey soil, right before construct the building or the foundation. The sand drains are installed by making holes vertically at selected intervals and then backfilled with sand after jetting out the unwanted soil. The drilling could be applied by one of the three ways; using rotary drilling, using continuous flight auger, using hollow steel pile or mandrel-driven pipes [1]. The surcharge will be applied at the top of the soil ground right after filling the drilling holes with sand. This surcharge will increase the pore water pressure at the soft clay which oblige the water to dissipate to the sand drains, the water flows from higher to lower potential energy. The water flows faster in the sand columns, sand drains, than soft soil which makes the sand columns target of lower potential energy [4]. Despite the sand drain or sand columns replace just (1-2) % of the soil, the bearing capacity of soil might be improved by more than 10% [11].

Radhakrishnan, G. 2010 has done a study to evaluate the effect of the sand drains on the consolidation settlement of clay soil. The results showed that the consolidation settlement are 9% and 31% for the without and with sand drains respectively during the first 10 months of the test. Moreover, the consolidation was 12% and 65% for the 20 months of the test. It obviously can be noticed the rapid increase in the rate of consolidation in case of using the sand drains.

Sand drains technique has some disadvantages which could be summarized by the following points [6]:

- The sand material should be precisely chosen to reach the desired drainage properties which could not be available near the construction site.
- During the sand filling, cavities could be happened due to sand bulking.
- Economic issues might appear due to large diameter of sand drains.
- The efficiency of the system might fall down due to the disturbance of soil happens during the sand drains installation.

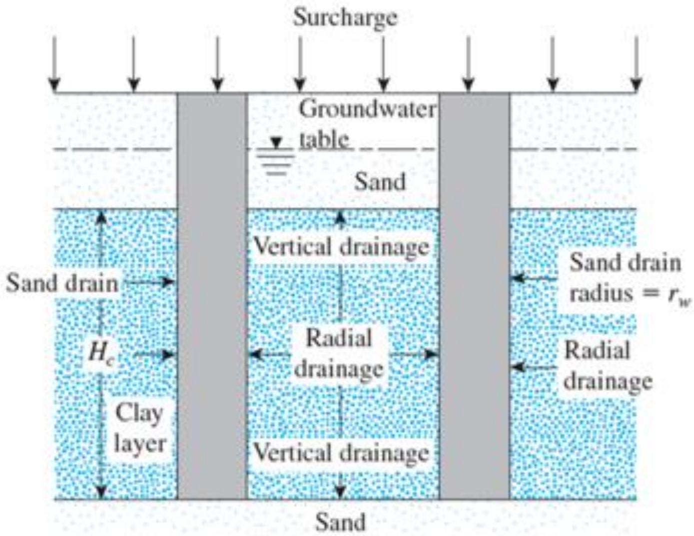

Figure 3 schematic figure illustrates the sand drains (After, Das 1983)

2.1.3.2 Wick Drains

Wick drains, or as it called pre-fabricated vertical drains or strip drains, are widely used all over the world in the past to accelerate the expected consolidation of soft soils [1]. The wick drains consist of plastic or paper core stripped with grooves and surrounding by a plastic or paper membrane as a geotextile filter [4]. The dimensions of the wick are (1-3) cm in width, (0.4-0.6) cm thick, and as long as it is required. The geotextile membrane is used to prevent the core from clogging by the soil particles. Prefabricated vertical drains are installed by using the vibratory hammed, similar to that used in installation of piles, with installation rate of (0.1-0.3) cm/sec. This technique has no effect on the bearing capacity of the soft soil or the shear strength, as it is useful only for accelerating the expected consolidation settlement before constructing the building or the suitable shallow foundation. This system accelerates the settlement faster than the stone columns, will be discussed later [22]. Wick drains system has some advantages over sand drains system for the following points [1] [4] [6].

- Prefabricated vertical drains system in much more economical than sand drain system. It costs about one quarter of the sand drain system, Bowles 1997.
- The wick drain can be installed for depths more than sand drains and could reach 30 m.
- The installation of wick drains does not need drilling processes.
- Wick drains system in way faster in installation than the sand drains.

- The installation process of the wick drains system exhibits lower disturbance compared to that generated from the sand drains system.

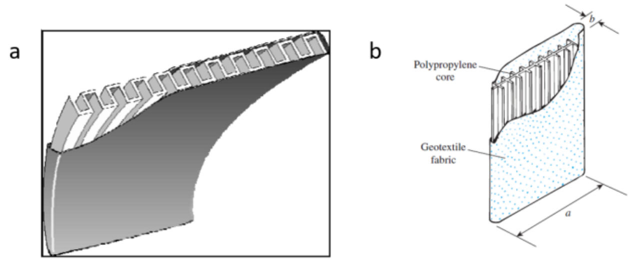

Figure 4 Typical Prefabricated vertical drains, (a After Das 1983, b After T. Stapelfeldt 2006)

2.2 soil improvement techniques by densification of soil

2.2.1 Stone Columns or granular Piles

This technique installation is similar to that of sand drains or sand columns but the fill material is gravel or stone instead the sand. The average grain size of the gravel is ranging from (6-40) mm [1]. The installation process includes drilling a hole with a diameter of 50 to 75 cm using water-jetting a vibroflot through the soft soil until reaching the harder soil. The gravel or stone then started to be filling the hole gradually and be compacted Consistently withdraw the vibroflot. The depth of drilling is about (5-8) m with spacing between the columns ranging from (120-300) cm center to center [4]. This technique increases the bearing capacity of shallow foundations on soft soil as well as reducing the consolidation settlement of soil. This method is still more effective with sand soil or clay soil with an unconfined shear strength of (10-50) KN/m^2. The reason behind that is that the soft soil weaker than that might not be able to withstand or introduce enough lateral support for the stone columns [1]. Generally, stone columns upgrade the performance of the soil by densifying the soil around the columns and sort of reinforcing the soil with harder and stiffer columns [3]. The water table has no effect on the role of the stone columns. The expected soil improvement of this technique depends on the type of soil as clarified in table 1.

Table 1 Expected effectiveness of stone columns regarding to Densification and Reinforcement [3]

Soil Description	Densification	Reinforcement
Gravel and sand <10% silt, no clay	Excellent	Very good
Sand with between 10 and 20% silt and <2% clay	Very good	Very good
Sand with >20% silt and nonplastic silt	Marginal (with large displacements)	Excellent
Clays	Not applicable	Excellent

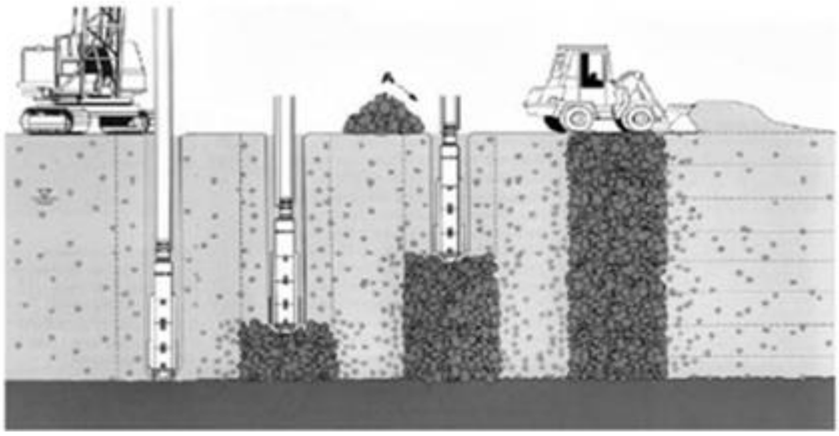

Figure 5 Stone columns installation process (After, Heinz J. Priebes, undated)

2.2.2 soil cement piles (SCP)

One of the not old soil improvement techniques is the soil cement pile. Its installation is somewhat similar to the stone columns installation process. A special drilling is required for this technique. The drill consists of special drill pit and shearing blade on top of it. The drill pit penetrates the soil into the required depth and the shear blade, which a pit larger than the drill bit, is rotating to insure a good mixing of soil with the cement slurry. When the desired depth is reached, the drill is withdrawn and cement slurry starts to be injected simultaneously and the shear blade keeps mixing the soil cutting with the injected cement. The dimensions limits of soil cement columns are about 1 m in diameter and about 10 m in length and could be up to 35 m is possible as well [4]. This technique is mainly used to reduce the consolidation settlement of the shallow foundation and increase the bearing capacity snd shear strength of soil. It reduces the settlement by about 80% depending on the number and length of these piles [4].

This soil cement column is somewhat similar to the stone columns, but the difference is that the stone columns shear strength depends on the internal friction between the stone particles and the confinement pressure from the soil around. Whilst, the strength of the soil cement columns is acquired from the cohesion [33].

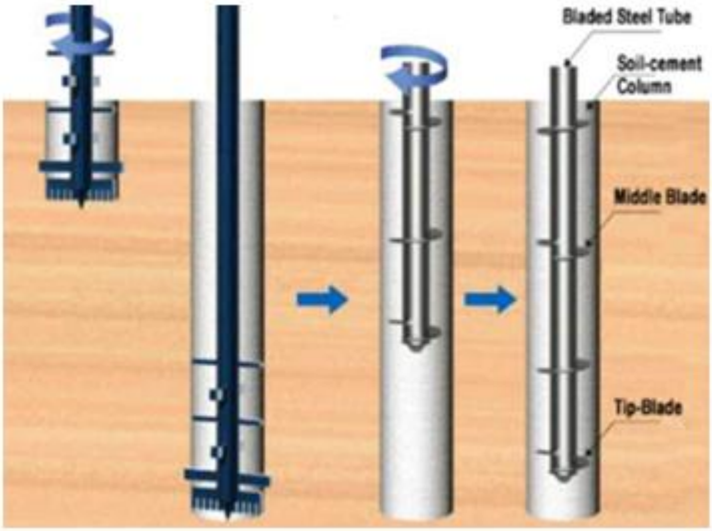

Figure 6 Soil cement piles installation process

2.2.3 Dynamic Compaction

This is technique is one of the easiest techniques to apply. It involves lifting and dropping a heavy load in a controlled pattern on the soil using a mobile crane. This can densify the soil and increase the shearing strength and bearing capacity of soil [2]. The most effected soils by this technique are classified as clayey or silty sands and gravel and. The effectiveness of this method decreases with increasing the silt and clay portion in the soil, Bowles 1997. The dynamic compaction could compact the soil up to 12.5 m depth [3].

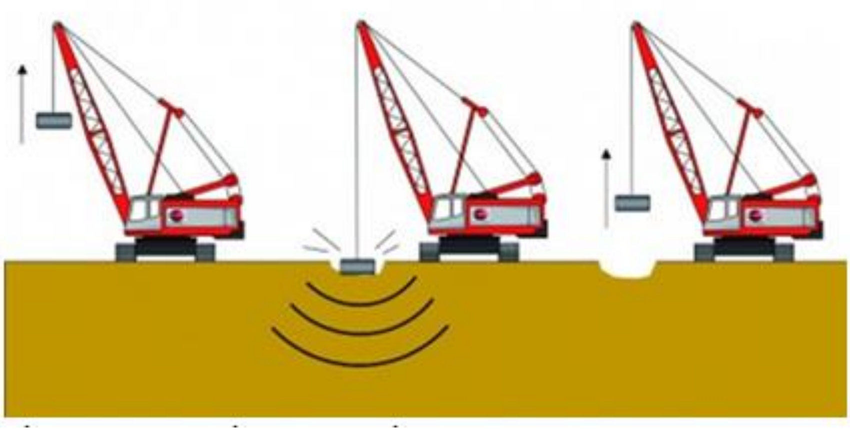

Figure 7 Dynamic Compaction process

2.2.4 Jet Grouting

This technique classified as one of the densification techniques because it densify the surrounding soil by injection of cement slurry. Conceptually, this method is somewhat similar to the soil cement pile. The installation process consists of drilling the soil with a special drill bit with high pressure water jets vertically and horizontally to excavate through the soil [4]. After that, the cement mortar is injected with high velocity laterally to be mixed with the surrounding soil. The soil around the excavation is being compacted continuously due to the grout bulb expansion as the cement injection increasing. This technique increases the shear strength of soil, as it reinforces the soil by these cement columns, and reducing the consolidation settlement before constructing the building. There are three different systems to drill the soil and inject the mortar cement, single, double, and triple fluid system [1]. The use of these system is dependent on the type soil. The details of these three system is clarified in details by Jaafar and Manar 2015 as in follow:

- Single fluid system

This system is more appropriate for sandy soil. This system is about applying high velocity cement mortar to cut and mix the soil.

- Double fluid system

This system fits the cohesion soil. It is a bit different from the previous system in applying the cement grout technique. The high velocity cement mortar is kind of surrounded by an air jet. This air jet increases the erosion efficiency of the system.

- Triple fluid system

This system is appropriate for cohesive soil which is stiffer than the soil needed in the double fluid system. This system is more efficient in erosion the soil because it consists two separate processes. First, a high velocity water surrounded with air jet is applied to erode the soil. Second, the cement slurry is injected from the lower jet with a low pressure and these two processes are applying simultaneously.

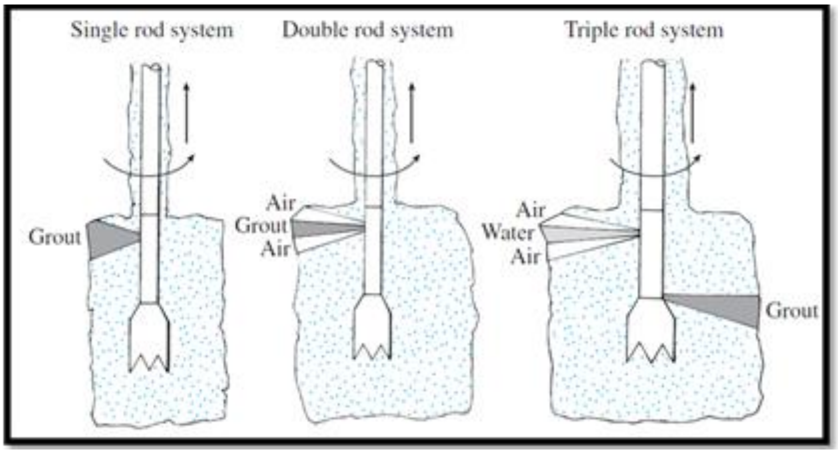

Figure 8 Jet grouting system processes (After, Das 1983)

2.2.5 Lime Piles

Lime piles or lime columns techniques is one of the best techniques used to improve the soft soils. Its installation process is somehow similar to the stone columns installation. It consists of vertical holes in soil and fill them with lime or lime and pozzolana. Lime piles have significant effect on increasing the shear strength and bearing cabacity of soil and decreasing the settlement of soil [38]. This technique has a significant effect to reduce the expantion potential of the expansive soil. Moreover, the shear strength of soft clay can be increases up to ten times when adding the lime with a percentage of 5 %. Sometimes, the lime is added as a mixture with sand with a percentage (1lime : 4sand) [2].

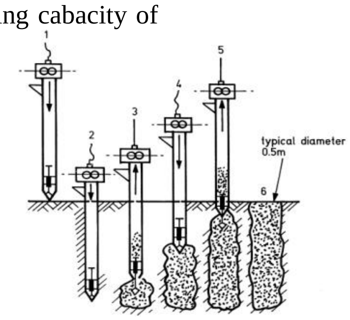

Figure 9 lime piles installation process (After, C.D.FRogers 1997)

2.3 Soil reinforcement by geotextile

Geotextile is one of the best materials to be used as a best soil reinforcement material due to its resistance against the harsh soil conditions. Sometimes it is called synthetic fiber and it is made up from, nylon, polyethylene, polyester, and polypropylene. The geotextile is available in forms of sheets, strips, or formed as geo-grids to reinforce the soil [4]. The hydraulic conductivity of the geotextile is much higher than that of the surrounding soil, which makes the water run from the soil toward the geotextile. Wick drains can be inserted vertically to upward the water to the ground and accelerate the consolidation settlement. The geotextile installation process consists of removing about 1 m from the soil and spreading the geotextile geo-grid and then backfilling the soil. The geo-grids could be as a single layer or multilayers to improve the bearing capacity of soil [3]. Geotextile can also applied as strips to increase the shear strength of soil. In this case, vertical and horizontal spaces should be designed to insure best effect on the shear strength. Moreover, geo-grids have additional use beneath the footings to increase the bearing capacity and increase the loaded area. The selection of the geotextile material should be Preceded by laboratory tests to study the strength and the durability of the material [2]. This technique is efficient enough to increase the bearing capacity of spread footing up to 2.5 times of the bearing capacity without reinforcement [3].

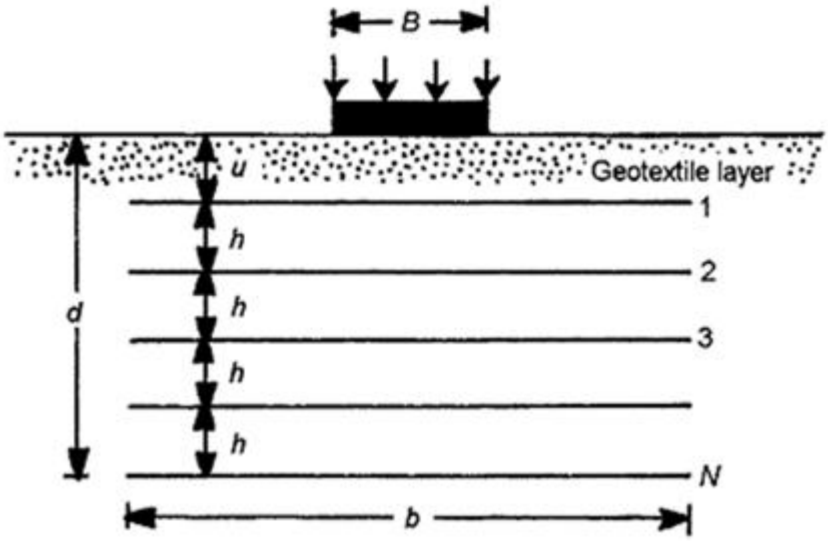

Figure 10 spread footing on a reinforced soil with geotextile

2.4 soil improvement with cement, lime, and fly-ash

This technique is totally dependent on increasing the bond between soil particle through the chemical additives, cement, lime, fly-ash, or combined of them. These chemical materials can be applied on the soil in three different manners [1]:

- Mixing the additive with the soil at the site with specific water content and then compaction is needed.
- Mixing the additive, soil, and water using plant and then backfill the soil with compaction. These two application methods are used up to 1.5 m depth of treatment, Bowles 1997.
- Inject the chemical additive into the soil with high pressure to a depth up to 5 m.

Adding the lime to the clay soil may increase the unconfined shear strength of soil from about 2100 KN/m^2 without lime to 2800 KN/m^2 with (3-5) % lime [1]. Likely, the cement has a positive effect on the shear strength of soil. Das 1983 made a table, table 2, to show the effect of the cement in improving the soil properties

Table 2 shear strength of soil with and without cement treatment (After, Das 1983)

Material	Unconfined compressive strength range	
	KN/m²	Ib/in²
Clay ,peat	Less than 350	Less than 50
Well-compacted sandy clay	70-280	10-40
Well-compacted gravel, sand , and clay mixtures	280-700	40-100
Soil-cement (10% cement by weight): Clay ,organic soils	Less thaN 350	Less than 50
Silts ,silty clays,very poorly graded sands, slightly organic soils	350-1050	50-150
Silty clays,sandy clays,very poorly graded sands, and gravels	700-1730	100-250
Silty sands, sandy clays,sands, and gravels	1730-3460	250-500
Well_graded sand -clay or gravel-sand -clay mixtures and sands and gravels	3460-10,350	500-1500

On the other hand, the use of fly ash improves the soil considering the shear strength [39] . In his study, four different ratios of fly ash were used, 5, 10, 15, and 20% at the optimum moisture content specified by standard proctor test. The shear strength parameters, cohesion and internal friction angle were measured and they were improved as the fly ash percent increases. The fly ash does not have bond properties in case of using it alone. For this reason, fly ash should be used as a secondary binder with lime or cement [11]. The optimum percent of fly ash to be used as a second binder with cement is about 12% to produce highest unconfined shear strength of soft soil [34].

III. CONCLUSION

Due to the lack of researches about the soil improvement techniques taking in consideration the shear strength, bearing capacity, and settlement, this paper has been done. This paper reviewed most of the techniques to improve the clayey soil regarding to increasing the strength and reducing the settlement. Few points can be concluded from this study:

- Soft clay is of the problematic soils that needs to be improved before getting started with constructing the foundations.
- Different technique has a different effect on the settlement. Some techniques accelerate the settlement before constructing the building and others are reducing the value of settlement.
- The examples about the techniques which reducing the value of settlement are:

✓ Soil removal and replacement.
✓ Stone columns.
✓ Soil cement piles.
✓ Dynamic compaction.
✓ Jet grouting.
✓ Lime piles.
✓ Soil reinforcement with geotextiles.
✓ Soil improvement by mixing with cement, lime, and fly ash.

- The techniques accelerate the settlement can be summarized in three techniques:

✓ Preloading and pre-compression technique.
✓ Sand drains.
✓ Wick drains.

- Some techniques are more effective than others in case of existing clayey soils. The most effective techniques to improve the properties of such a soil are preloading, stone columns, soil reinforcement with geotextiles, dynamic compaction, soil improvement with additives, and sand and wick drains columns.
- More studies needed about the soil removal and replacement technique to estimate the depth of replaced soil because it still depends on the engineer experience.

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