

STATE OF THE ART REVIEW

SOIL STABILIZATION METHODS AND MATERIALS

IN ENGINEERING PRACTICE



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PREFACE

The knowledge of soil Stabilization in geotechnical engineering has been well documented. Journal articles and text books on stabilization technology are available to the students, practicing and consulting engineers in the field of geotechnical engineering. This state of the art review brings up to date trends in stabilization practice with the main focus in stabilization methods and materials. The first part of this review discusses the effect of various binders on stabilized soils. The second part describes stabilization methods and equipment. The review describes in brief modernized stabilization methods and equipment to practicing engineers. For detailed information about the subject matter, readers should refer to the cited authors available in the reference list.

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1.0 INTRODUCTION

Site feasibility study for geotechnical projects is of far most beneficial before a project can take off. Site survey usually takes place before the design process begins in order to understand the characteristics of subsoil upon which the decision on location of the project can be made. The following geotechnical design criteria have to be considered during site selection.

- Design load and function of the structure.
- Type of foundation to be used.
- Bearing capacity of subsoil.

In the past, the third bullet played a major in decision making on site selection. Once the bearing capacity of the soil was poor, the following were options:

- Change the design to suit site condition.
- Remove and replace the in situ soil.
- Abandon the site.

Abandoned sites due to undesirable soil bearing capacities dramatically increased, and the outcome of this was the scarcity of land and increased demand for natural resources. Affected areas include those which were susceptible to liquefaction and those covered with soft clay and organic soils. Other areas were those in a landslide and contaminated land. However, in most geotechnical projects, it is not possible to obtain a construction site that will meet the design requirements without ground modification. The current practice is to modify the engineering properties of the native problematic soils to meet the design specifications. Nowadays, soils such as, soft clays and organic soils can be improved to the civil engineering requirements. This state of the art review focuses on soil stabilization method which is one of the several methods of soil improvement.

Soil stabilization aims at improving soil strength and increasing resistance to softening by water through bonding the soil particles together, water proofing the particles or combination of the two (Sherwood, 1993). Usually, the technology provides an alternative provision structural solution to a practical problem. The simplest stabilization processes are compaction and drainage (if water drains out of wet soil it becomes stronger). The other process is by improving gradation of particle size and further

improvement can be achieved by adding binders to the weak soils (Rogers et al, 1996). Soil stabilization can be accomplished by several methods. All these methods fall into two broad categories (FM 5-410) namely;

- mechanical stabilization

Under this category, soil stabilization can be achieved through physical process by altering the physical nature of native soil particles by either induced vibration or compaction or by incorporating other physical properties such as barriers and nailing. Mechanical stabilization is not the main subject of this review and will not be further discussed.

- chemical stabilization

Under this category, soil stabilization depends mainly on chemical reactions between stabilizer (cementitious material) and soil minerals (pozzolanic materials) to achieve the desired effect. A chemical stabilization method is the fundamental of this review and, therefore, throughout the rest of this report, the term soil stabilization will mean *chemical stabilization*.

Through soil stabilization, unbound materials can be stabilized with cementitious materials (cement, lime, fly ash, bitumen or combination of these). The stabilized soil materials have a higher strength, lower permeability and lower compressibility than the native soil (Keller brochure 32-01E). The method can be achieved in two ways, namely; (1) in situ stabilization and (2) ex-situ stabilization. Note that, stabilization not necessary a magic wand by which every soil properties can be improved for better (Ingles and Metcalf, 1972). The decision to technological usage depends on which soil properties have to be modified. The chief properties of soil which are of interest to engineers are volume stability, strength, compressibility, permeability and durability (Ingles and Metcalf, 1972; Sherwood, 1993; EuroSoilStab, 2002). For a successful stabilization, a laboratory tests followed by field tests may be required in order to determine the engineering and environmental properties. Laboratory tests although may produce higher strength than corresponding material from the field, but will help to assess the effectiveness of stabilized materials in the field. Results from the laboratory tests, will enhance the knowledge on the choice of binders and amounts (EuroSoilStab, 2002).

2.0 COMPONENTS OF STABILIZATION

Soil stabilization involves the use of stabilizing agents (binder materials) in weak soils to improve its geotechnical properties such as compressibility, strength, permeability and durability. The components of stabilization technology include soils and or soil minerals and stabilizing agent or binders (cementitious materials).

2.1 Soils

Most of stabilization has to be undertaken in soft soils (silty, clayey peat or organic soils) in order to achieve desirable engineering properties. According to Sherwood (1993) fine-grained granular materials are the easiest to stabilize due to their large surface area in relation to their particle diameter. A clay soil compared to others has a large surface area due to flat and elongated particle shapes. On the other hand, silty materials can be sensitive to small change in moisture and, therefore, may prove difficult during stabilization (Sherwood, 1993). Peat soils and organic soils are rich in water content of up to about 2000%, high porosity and high organic content. The consistency of peat soil can vary from muddy to fibrous, and in most cases, the deposit is shallow, but in worst cases, it can extend to several meters below the surface (Pousette, et al 1999; Cortellazzo and Cola, 1999; Åhnberg and Holm, 1999). Organic soils have high exchange capacity; it can hinder the hydration process by retaining the calcium ions liberated during the hydration of calcium silicate and calcium aluminate in the cement to satisfy the exchange capacity. In such soils, successful stabilization has to depend on the proper selection of binder and amount of binder added (Hebib and Farrell, 1999; Lahtinen and Jyrävä, 1999, Åhnberg et al, 2003).

2.2 Stabilizing Agents

These are hydraulic (primary binders) or non-hydraulic (secondary binders) materials that when in contact with water or in the presence of pozzolanic minerals reacts with water to form cementitious composite materials. The commonly used binders are:

- cement
- lime
- fly ash

- blast furnace slag

2.2.1 Cement

Cement is the oldest binding agent since the invention of soil stabilization technology in 1960's. It may be considered as primary stabilizing agent or hydraulic binder because it can be used alone to bring about the stabilizing action required (Sherwood, 1993; EuroSoilStab, 2002). Cement reaction is not dependent on soil minerals, and the key role is its reaction with water that may be available in any soil (EuroSoilStab, 2002). This can be the reason why cement is used to stabilize a wide range of soils. Numerous types of cement are available in the market; these are ordinary Portland cement, blast furnace cement, sulfate resistant cement and high alumina cement. Usually the choice of cement depends on type of soil to be treated and desired final strength.

Hydration process is a process under which cement reaction takes place. The process starts when cement is mixed with water and other components for a desired application resulting into hardening phenomena. The hardening (setting) of cement will enclose soil as glue, but it will not change the structure of soil (EuroSoilStab, 2002). The hydration reaction is slow proceeding from the surface of the cement grains and the centre of the grains may remain unhydrated (Sherwood, 1993). Cement hydration is a complex process with a complex series of unknown chemical reactions (MacLaren and White, 2003). However, this process can be affected by

- presence of foreign matters or impurities
- water-cement ratio
- curing temperature
- presence of additives
- specific surface of the mixture.

Depending on factor(s) involved, the ultimate effect on setting and gain in strength of cement stabilized soil may vary. Therefore, this should be taken into account during mix design in order to achieve the desired strength. Calcium silicates, C_3S and C_2S are the two main cementitious properties of ordinary Portland cement responsible for strength development (Al-Tabbaa and Perera, 2005; EuroSoilStab, 2002). Calcium hydroxide is another hydration product of Portland cement that further reacts with pozzolanic

materials available in stabilized soil to produce further cementitious material (Sherwood, 1993). Normally the amount of cement used is small but sufficient to improve the engineering properties of the soil and further improved cation exchange of clay. Cement stabilized soils have the following improved properties:

- decreased cohesiveness (Plasticity)
- decreased volume expansion or compressibility
- increased strength (PCA-IS 411, 2003).

2.2.2 Lime

Lime provides an economical way of soil stabilization. Lime modification describes an increase in strength brought by cation exchange capacity rather than cementing effect brought by pozzolanic reaction (Sherwood, 1993). In soil modification, as clay particles flocculates, transforms natural plate like clays particles into needle like interlocking metalline structures. Clay soils turn drier and less susceptible to water content changes (Roger et al, 1993). Lime stabilization may refer to pozzolanic reaction in which pozzolana materials reacts with lime in presence of water to produce cementitious compounds (Sherwood, 1993, EuroSoilStab, 2002). The effect can be brought by either quicklime, CaO or hydrated lime, Ca (OH)₂. Slurry lime also can be used in dry soils conditions where water may be required to achieve effective compaction (Hicks, 2002). Quicklime is the most commonly used lime; the followings are the advantages of quicklime over hydrated lime (Rogers et al, 1996).

- higher available free lime content per unit mass
- denser than hydrated lime (less storage space is required) and less dust
- generates heat which accelerate strength gain and large reduction in moisture content according to the reaction equation below



Quicklime when mixed with wet soils, immediately takes up to 32% of its own weight of water from the surrounding soil to form hydrated lime; the generated heat accompanied by this reaction will further cause loss of water due to evaporation which in turn results into increased plastic limit of soil i.e. drying out and absorption (EuroSoilStab, 2002; Sherwood, 1993). The effect can be explained from Figure 1 for

soil at a moisture content of 35% and plastic limit 25%. Addition of 2% lime will change the plastic limit to 40% so that the moisture content of the soil will be 5% below plastic limit instead of 10% above plastic limit (Sherwood, 1993). Sherwood (1993) investigated the decrease in plasticity as brought about in first instance by cation exchange in which cations of sodium and hydrogen are replaced by calcium ions for which the clay mineral has a greater water affinity. Even in soils (e.g. calcareous soils) where, clay may be saturated with calcium ions, addition of lime will increase pH and hence increase the exchange capacity. Like cement, lime when reacts with wet clay minerals result into increased pH which favors solubility of siliceous and aluminous compounds. These compounds react with calcium to form calcium silica and calcium alumina hydrates, a cementitious product similar to those of cement paste. Natural pozzolanas materials containing silica and alumina (e.g. clay minerals, pulverized fly ash, PFA, blast furnace slag) have great potential to react with lime.

Lime stabilizations technology is mostly widely used in geotechnical and environmental applications. Some of applications include encapsulation of contaminants, rendering of backfill (e.g. wet cohesive soil), highway capping, slope stabilization and foundation improvement such as in use of lime pile or lime-stabilized soil columns (Ingles and Metcalf, 1972). However, presence of sulphur and organic materials may inhibit the lime stabilization process. Sulphate (e.g. gypsum) will react with lime and swell, which may have effect on soil strength.

2.2.3 Fly–Ash

Fly ash is a byproduct of coal fired electric power generation facilities; it has little cementitious properties compared to lime and cement. Most of the fly ashes belong to secondary binders; these binders cannot produce the desired effect on their own. However, in the presence of a small amount of activator, it can react chemically to form cementitious compound that contributes to improved strength of soft soil. Fly ashes are readily available, cheaper and environmental friendly. There are two main classes of fly ashes; class C and class F (Bhuvaneshwari et al, 2005, FM 5-410). Class C fly ashes are produced from burning subbituminous coal; it has high cementing properties because of high content of free CaO. Class C from lignite has the highest CaO (above 30%) resulting

in self-cementing characteristics (FM 5-410). Class F fly ashes are produced by burning anthracite and bituminous coal; it has low self-cementing properties due to limited

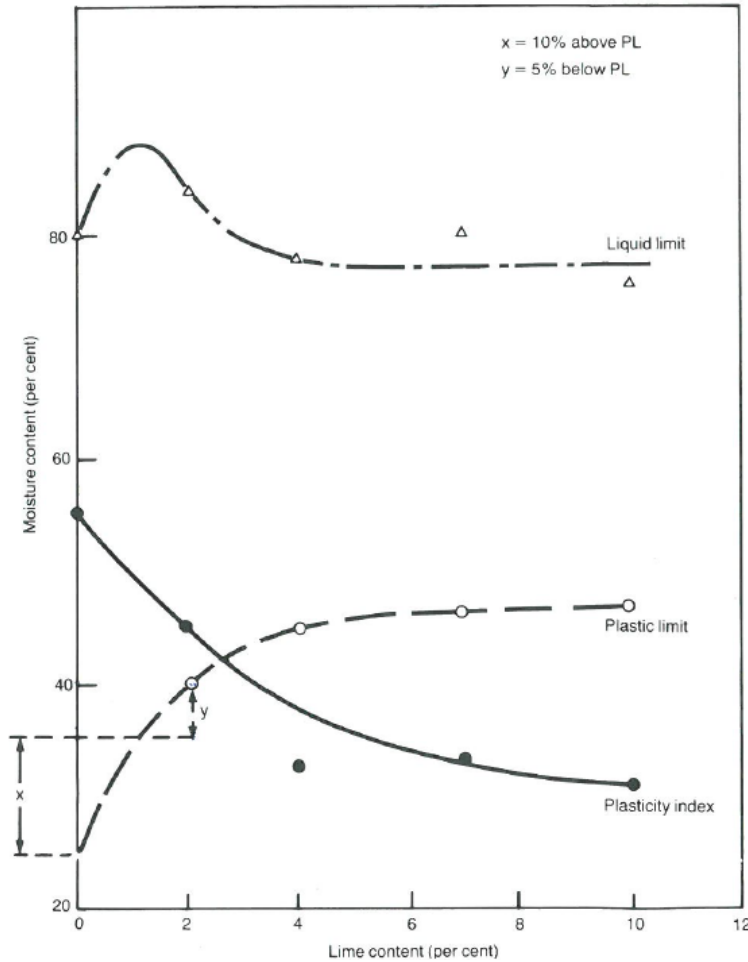


Figure 1: Effect of the addition of the lime on plasticity properties of London clay (Sherwood, 1993)

amount of free CaO available for flocculation of clay minerals and thus require addition of activators such as lime or cement. The reduction of swell potential achieved in fly ashes treated soil relates to mechanical bonding rather than ionic exchange with clay minerals (Mackiewicz and Ferguson, 2005). However, soil fly ash stabilization has the following limitations (White, 2005):



Figure 2: A road reclaimer mixes soil with moist conditioned fly ash (Beeghly, 2003).

- Soil to be stabilized shall have less moisture content; therefore, dewatering may be required.
- Soil-fly ash mixture cured below zero and then soaked in water are highly susceptible to slaking and strength loss
- Sulfur contents can form expansive minerals in soil-fly ash mixture, which reduces the long term strength and durability.

2.2.4 Blast Furnace Slags

These are the by-product in pig iron production. The chemical compositions are similar to that of cement. It is however, not cementitious compound by itself, but it possesses latent hydraulic properties which upon addition of lime or alkaline material the hydraulic properties can develop (Sherwood, 1993; Åhnberg et al, 2003). Depending on cooling system, Sherwood (1993) itemized slag in three forms, namely:

- Air-cooled slag

Hot slag after leaving the blast furnace may be slowly cooled in open air, resulting into crystallized slag which can be crushed and used as aggregate.

- Granulated (merit 5000) or Pelletised slag

Quenching (i.e. sudden cooling with water or air) of hot slag may result into formation of vitrified slag. The granulated blast furnace slag or Merit 5000 (commonly known in Sweden) is a result of use of water during quenching process, while, the use of air in the process of quenching may result into formation of pelletised slag.

- Expanded slag

Under certain conditions, steam produced during cooling of hot slag may give rise to expanded slag.

2.2.5 Pozzolanas

Pozzolanas are siliceous and aluminous materials, which in itself possess little or no cementitious value, but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (ASTM 595). Clay minerals such as kaolinite, montmorillonite, mica and illite are pozzolanic in nature. Artificial pozzolanas such as ashes are products obtained by heat treatment of natural materials containing pozzolanas such as clays, shales and certain silicious rocks. Plants when burnt, silica taken from soils as nutrients remains behind in the ashes contributing to pozzolanic element. Rice husk ash and rice straw and bagasse are rich in silica and make an excellent pozzolana (Sherwood, 1993).

2.3 Factors Affecting the Strength of Stabilized Soil

Presence of organic matters, sulphates, sulphides and carbon dioxide in the stabilized soils may contribute to undesirable strength of stabilized materials (Netterberg and Paige-Green, 1984, Sherwood, 1993).

2.3.1 Organic Matter

In many cases, the top layers of most soil constitute large amount of organic matters. However, in well drained soils organic matter may extend to a depth of 1.5 m (Sherwood, 1993). Soil organic matters react with hydration product e.g. calcium hydroxide (Ca(OH)₂) resulting into low pH value. The resulting low pH value may retard the

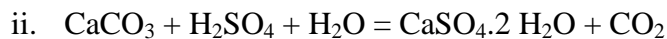
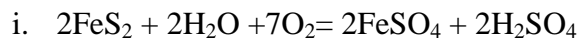
hydration process and affect the hardening of stabilized soils making it difficult or impossible to compact.

2.3.2 Sulphates

The use of calcium-based stabilizer in sulphate-rich soils causes the stabilized sulphate rich soil in the presence of excess moisture to react and form calcium sulphoaluminate (ettringite) and or thamausite, the product which occupy a greater volume than the combined volume of reactants. However, excess water to one initially present during the time of mixing may be required to dissolve sulphate in order to allow the reaction to proceed (Little and Nair, 2009; Sherwood, 1993).

2.3.3 Sulphides

In many of waste materials and industrial by-product, sulphides in form of iron pyrites (FeS_2) may be present. Oxidation of FeS_2 will produce sulphuric acid, which in the presence of calcium carbonate, may react to form gypsum (hydrated calcium sulphate) according to the reactions (i) and (ii) below



The hydrated sulphate so formed, and in the presence of excess water may attack the stabilized material in a similar way as sulphate (Sherwood, 1993). Even so, gypsum can also be found in natural soil (Little and Nair, 2009).

2.3.4 Compaction

In practice, the effect of addition of binder to the density of soil is of significant importance. Stabilized mixture has lower maximum dry density than that of unstabilized soil for a given degree of compaction. The optimum moisture content increases with increasing binders (Sherwood, 1993). In cement stabilized soils, hydration process takes place immediately after cement comes into contact with water. This process involves hardening of soil mix which means that it is necessary to compact the soil mix as soon as possible. Any delay in compaction may result in hardening of stabilized soil mass and therefore extra compaction effort may be required to bring the same effect. That may lead to serious bond breakage and hence loss of strength. Stabilized clay soils are more likely

to be affected than other soils (Figure 1) due to alteration of plasticity properties of clays (Sherwood, 1993). In contrary to cement, delay in compaction for lime-stabilized soils may have some advantages. Lime stabilized soil require mellowing period to allow lime to diffuse through the soil thus producing maximum effects on plasticity. After this period, lime stabilized soil may be remixed and given its final compaction resulting into remarkable strength than otherwise (Sherwood, 1993).

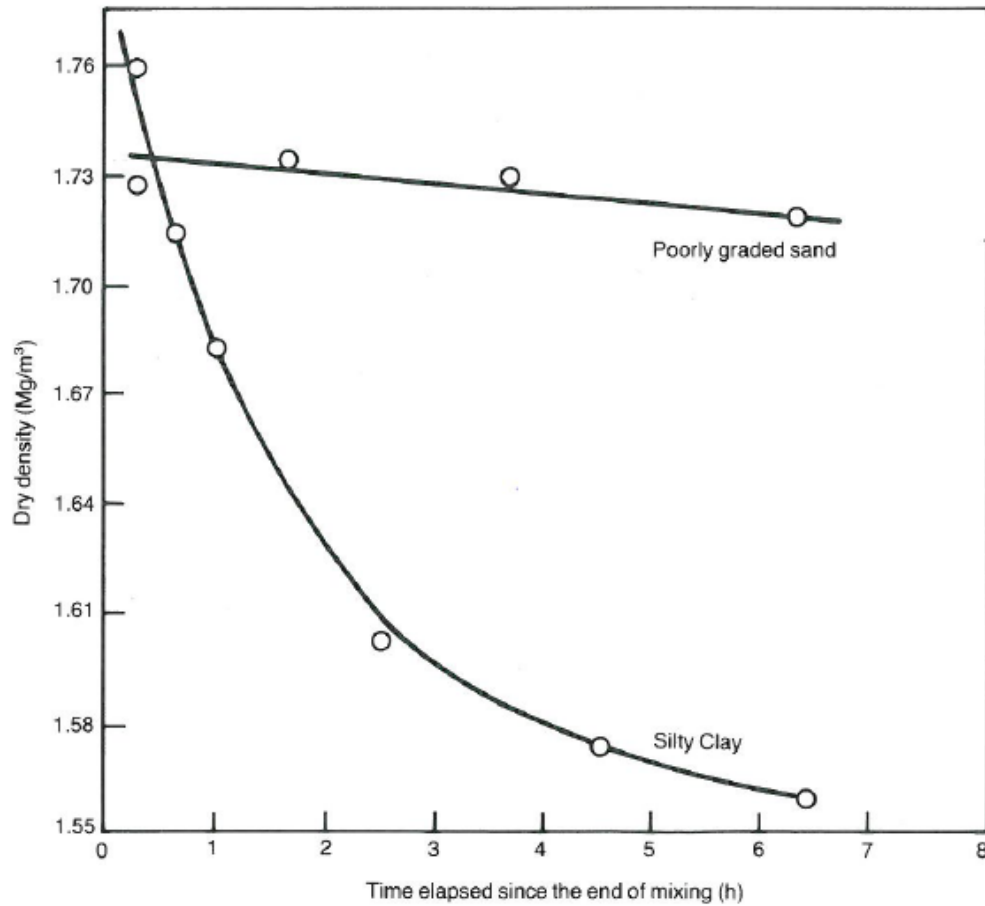


Figure 3: Dry density versus time elapsed since the end of mixing of two material stabilized with 10% cement (Sherwood, 1993)

2.3.5 Moisture Content

In stabilized soils, enough moisture content is essential not only for hydration process to proceed but also for efficient compaction. Fully hydrated cement takes up about 20% of its own weight of water from the surrounding (Sherwood, 1993); on other hand, Quicklime (CaO) takes up about 32% of its own weight of water from the surrounding (Roger et al, 1993; Sherwood, 1993). Insufficient moisture content will cause binders to

compete with soils in order to gain these amounts of moisture. For soils with great soil-water affinity (such as clay, peat and organic soils), the hydration process may be retarded due to insufficient moisture content, which will ultimately affect the final strength.

2.3.6 Temperature

Pozzolanic reaction is sensitive to changes in temperature. In the field, temperature varies continuously throughout the day. Pozzolanic reactions between binders and soil particles will slow down at low temperature and result into lower strength of the stabilized mass. In cold regions, it may be advisable to stabilize the soil during the warm season (Sherwood, 1993; Maher et al, 1994).

2.3.7 Freeze-Thaw and Dry-Wet Effect

Stabilized soils cannot withstand freeze-thaw cycles. Therefore, in the field, it may be necessary to protect the stabilized soils against frost damage (Maher et al, 2003; Al-tabbaa and Evans, 1998).

Shrinkage forces in stabilized soil will depend on the chemical reactions of the binder. Cement stabilized soil are susceptible to frequent dry-wet cycles due to diurnal changes in temperature which may give rise to stresses within a stabilized soil and, therefore, should be protected from such effects (Sherwood, 1993; Maher et al, 2003).

3.0 STABILIZATION METHODS

3.1 In-Situ Stabilization

The method involves on site soil improvement by applying stabilizing agent without removing the bulk soil. This technology offer benefit of improving soils for deep foundations, shallow foundations and contaminated sites. Planning of the design mix involves the selection and assessment of engineering properties of stabilized soil and improved ground. The purpose is to determine the dimensions of improved ground on the basis of appropriate stability and settlement analyses to satisfy the functional requirements of the supported structure (Keller Inc.). The technology can be accomplished by injection into soils a cementitious material such cement and lime in dry or wet forms. The choice to either use dry or wet deep mixing methods depend among other things; the in-situ soil conditions, in situ moisture contents, effectiveness of binders to be used, and the nature of construction to be founded. Depending on the depth of treatment, the in situ stabilization may be regarded as either deep mixing method or mass stabilization.

3.1.1 Deep Mixing Method

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 is injected into the ground and blended with in situ soft soils (clay, peat or organic soils) by mechanical or rotary mixing tool (Porbaha et al, 2005; EuroSoilStab, 2002). Depending on applications, the following patterns may be produced (Figure 4); single patterns, block patterns, panel pattern or stabilized grid pattern (EuroSoilStab, 2002). Note that, the aim is to produce the stabilized soil mass which may interact with natural soil and not, to produce too stiffly stabilized soil mass like a rigid pile which may independently carry out the design load. The increased strength and stiffness of stabilized soil should not, therefore, prevent an effective interaction and load distribution between the stabilized soil and natural soil (EuroSoilStab, 2002). Thus the design load should be distributed and carried out partly by natural soil and partly by stabilized soil mass (column).

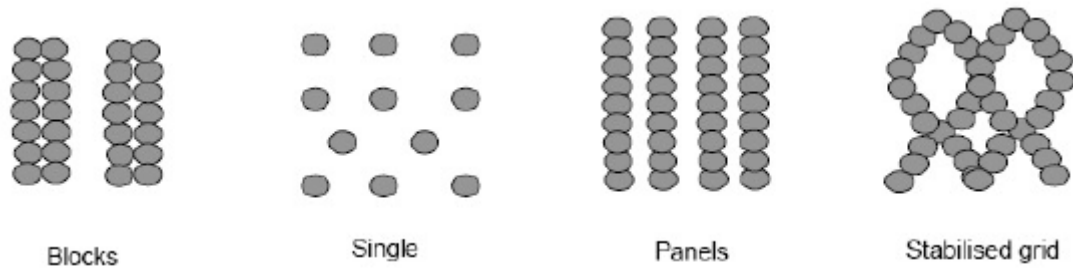


Figure 4: Typical patterns of deep soil mixing (EuroSoilStab, 2002)

Wet Mixing

Applications of wet deep mixing involve binder turned into slurry form, which is then injected into the soil through the nozzles located at the end of the soil auger (Massarsch and Topolnicki, 2005). The mixing tool comprise of drilling rod, transverse beams and a drill end with head. There are some modifications to suit the need and applications. For instance, the Trench cutting Re-mixing deep method (TRD) developed by circa Japan, in 1993 provides an effective tool for construction of continuous cutoff wall without the need for open trench. The method uses a crawler-mounted, chainsaw-like mixing tool to blend in-situ soil with cementitious binder to create the soil-cement wall. It further consists of a fixed post on which cutting, scratching teeth ride on a rotating chain and injection ports deliver grout into treatment zone. Wall depths up to 45 m having width between 0.5 m and 0.9 m are achievable. The wall quality for groundwater barrier is high with permeability between 1×10^{-6} and 1×10^{-8} cm/s (www.HaywardBaker.com). Similar to TRD, in 1994, Germany developed the FMI (Misch-Injektionsverfahren) machine. The FMI machine has a special cutting arm (trencher), along which cutting blades are rotated by two chain system. The cutting arm can be inclined up to 80 degrees and is dragged through the soil behind the power unit (Stocker and Seidel, 2005). Like TRD, the soil is not excavated, but mixed with binder which is supplied in slurry form through injection pipes and outlets mounted along the cutting arm (Figure 5).



Figure 5: The FMI and TRD–Trenching machine for construction of deep walls (Massarsch and Topolnicki, 2005; Hayward Baker Inc.)



Figure 6: Parts of wet mixing tool showing injection of slurry into the soil (Porbaha et al, 2005)

Dry Mixing

Dry mixing (DM) method is clean, quiet with very low vibration and produces no spoil for disposal (Hayward Baker Inc). It has for many years extensively used in Northern Europe and Japan. The method involves the use of dry binders injected into the soil and thoroughly mixed with moist soil (Figure 13). The soil is premixed using specialized tool during downward penetration, until it reaches the desired depth. During withdrawal of the mixing tool, dry binder are then injected and mixed with premixed soil leaving behind a moist soil mix column. In Scandinavians countries and Sweden in particular, this method is referred to as Lime Cement Column (LCC), whereas, in Italy, the method is termed as Trevimix and in Japan, the same technology is called dry jet mixing (DJM) (Bruce et al, 1996; Yasui and Yokozawa, 2005).



Figure 7: Bauer cutter soil mixing (Fiorotto et al, 2005)

A typical DM machine consists of track mounted installation rig and a drill motor. Binder is fed into compressed air through the hose into mixing shaft to the outlet of mixing shaft into the ground (Figure 13). Powdery binders under compressed air are injected into soft ground without processing into slurry form. Blade rotates creating a cavity in the soil in which air and binders fill in during withdrawal. During construction, the most efficient sequence is to work the stabilizing machine within its operational radius as much as possible (EuroSoilStab, 2002). Figure 9 and Figure 10 shows the construction principle and detail of mixing blade (Yasui and Yokozawa, 2005; EuroSoilStab, 2002). The native soil is thoroughly mixed with this compressed binder resulting into hardened column within the ground; the column size up to 1.5 meter diameter may be achieved with a maximum depth up to 40 m (EuroSoilStab, 2002). In sensitive soils, penetration induced vibration may cause loss of soil strength; therefore, it may be required to inject some of the binder into the ground during penetration. A wide range of strength can be obtained from low strength to high strength through regulation of amount of binder. High improved ratio can be achieved by overlapping mixing or interlocking the column. This

method has wide application from embankment stabilization, slope protection to foundation improvement and liquefaction mitigation (Yasui and Yokozawa, 2005). It should be noted that, the effectiveness of the method depends on percentage moisture of the soil. Thus, the method is not effective in sandy layer with low water content of less than 30% (Nozu, 2005).

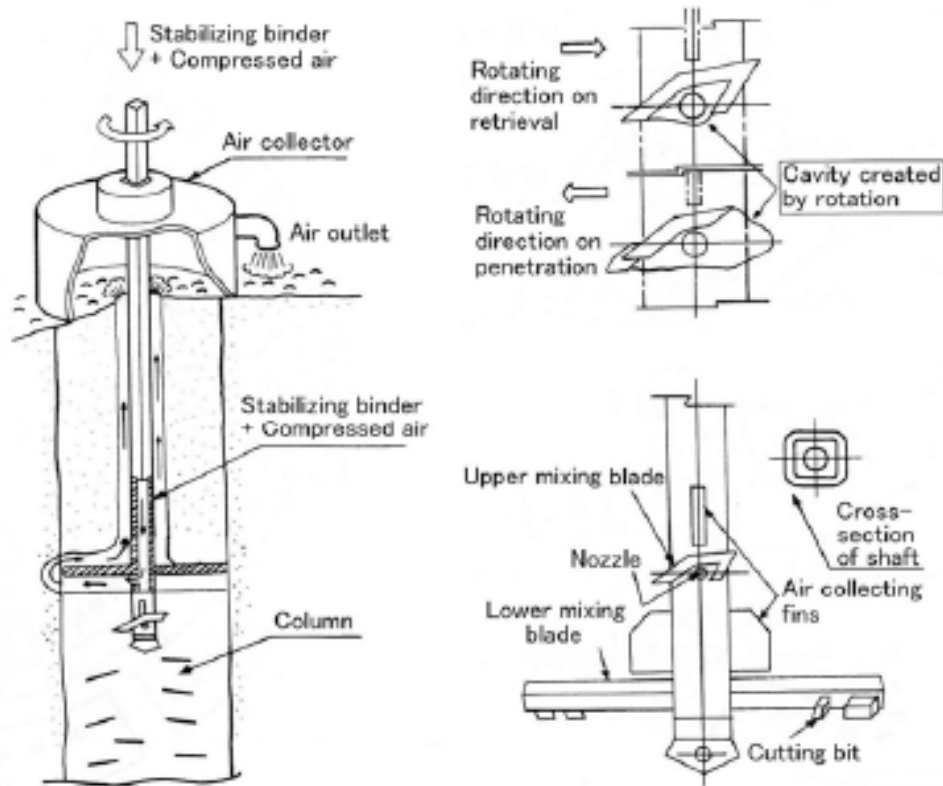


Figure 8: Schematic diagram of construction principle and structure of mixing blade (Yasui and Yokozawa, 2005)

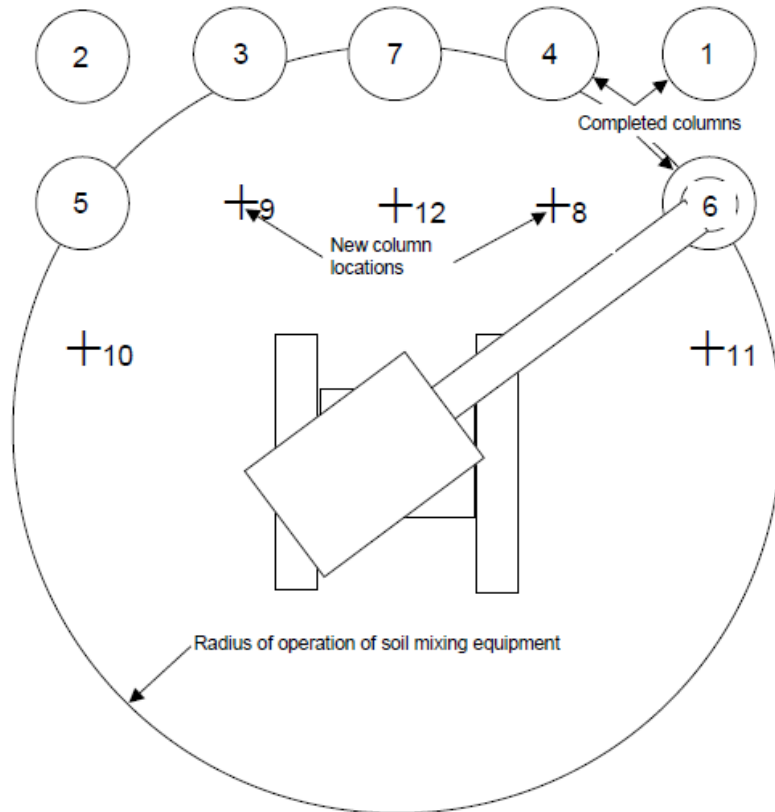


Figure 9: Sequence of operation for deep soil mixed columns (EuroSoilStab, 2002)



Figure 10: Nordic dry mixing "standard" tool (Larsson, 2005)



Figure 11: Nordic modified dry mixing tool (Larsson, 2005)



Figure 12: Injection of dry binder into the soil from the mixing tool (Keller)

3.1.2 Quality Control and Quality Assurance

In deep mixing methods, automatic quality control and quality assurance (QC and QA) has to be implemented. A variety of installed monitoring instruments in the mixing machine and binder feeder may help to control column positions, mixing proportional, binder quantity, penetration and retrieval speed (Stocker and Seidel, 2005; Yasui and Yokozawa, 2005) (Figure 14).



Figure 13: Online quality control/quality assurance of construction parameters (Stocker and Seidel, 2005)

3.1.3 Applications

For geotechnical and environmentally purposes, the typical application of deep mixing methods can be grouped into two main categories:

- Non-structural purposes
 - Ground cutoff wall
 - Dewatering wall
 - Containment of contaminants
 - Secondary containment
- Structural purposes
 - Deep and shallow foundation
 - Tunnel and Retaining wall (stabilization of cuts and open excavation)

Porbaha et al (2005) categorized deep mixing application into six main applications, namely;

- Hydraulic barrier systems
- Retaining wall systems
- Foundation support systems
- Excavation support systems
- Liquefaction/Seismic mitigation systems
- Environmental remediation systems

Foundation support systems

Application of deep mixing methods in foundation engineering includes foundation systems to heavy machinery, highway embankment, storage tanks, dome silo and rail systems (Figure 15-Figure 17) for both shallow and deep foundations.



Figure 14: Railroad Bridge supported by deep mixing column at San Francisco International Airport (Porbaha et al, 2005)

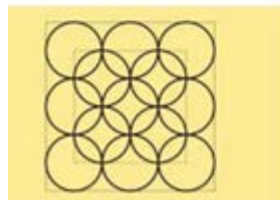
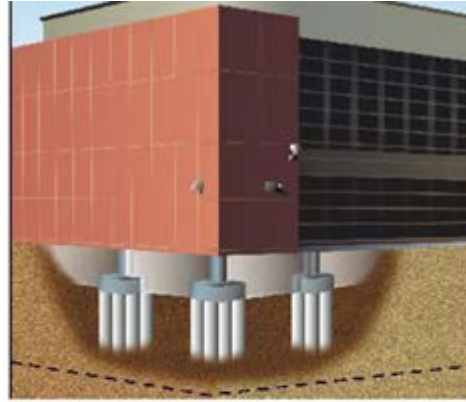


Figure 15: Application of deep mixing in building foundation (Nozu, 2005)



Figure 16: Foundation for A2 Motorway Bridge near Katowice (Massarsch and Topolnicki, 2005)

Hydraulic barrier support systems

The application of deep mixing in hydraulic structures, aims at control of flood, seepage and piping through the installation of cut-off wall systems. Figure 18 shows the application of TRD in construction of a groundwater barrier at Herbert Hoover dike in USA.



Figure 17: Top: TRD equipment at work, Bottom: Inspection of the exposed TRD wall at Herbert Hoover Dike surrounding Lake Okeechobee in southeastern Florida (Hayward Baker Inc.)

Retaining wall systems

A free standing wall (Figure 19) can be constructed using DM which may be used to retain soil behind it. These retaining walls (Gravity or reinforced wall systems) are most useful for river front, sea wall for Ports and Harbor, secant walls, water bulkhead and open excavations.



Figure 18: Reinforced deep mixing retaining wall (Porbaha et al, 2005)

Excavation support systems

Under this category, the applications include the construction of support to open excavations and underground constructions such as braced excavations, building excavation, cut and cover tunnel, trenches for railway tracks. All of these may use deep mixing to construct retaining wall for maintaining the open excavations (Figure 20).

Seismic and Liquefaction mitigation systems

Application of deep mixing may include seismic retrofit of dam foundation, alleviation of lateral spreading, liquefaction mitigation of culvert foundation and river banks, strengthening around an excavation and levee, stabilization of dune deposits, see Figure 24–Figure 25 (Porbaha et al, 2005; Yasui and Yokozawa, 2005). The main objective of stabilization in such application is to reduce pore water pressures, to increase the shear strength of the soils that could liquefy (EuroSoilStab, 2002) and or to minimize the propagation of waves in the super-and substructure of the infrastructure systems, see Figure 21–Figure 23 (Holm et al, 2002).



Figure 19: Top: Trench excavation railroad for an Alameda corridor project. Bottom: Structural cutoff wall during construction of new facility at Harvard University, Cambridge (Porbaha et al, 2005)

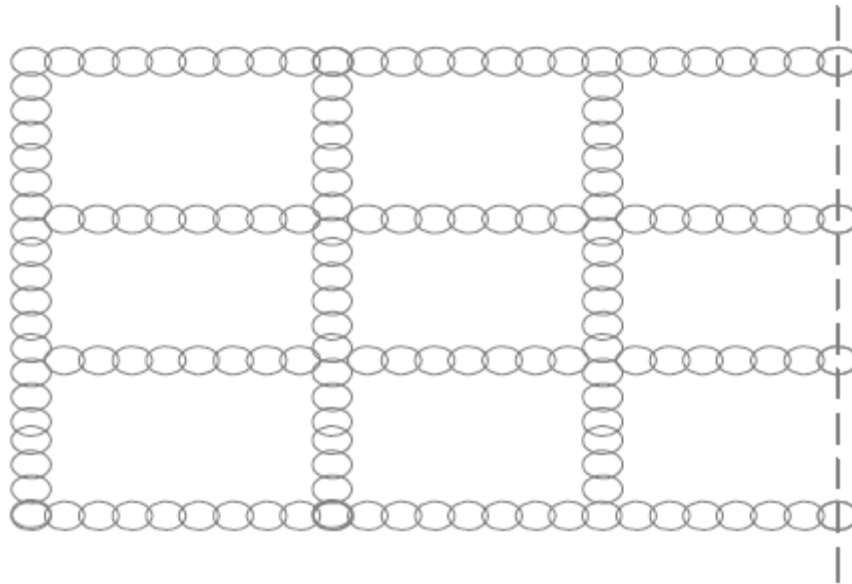


Figure 20: Example of panel pattern in liquefaction mitigation (EuroSoilStab, 2002)

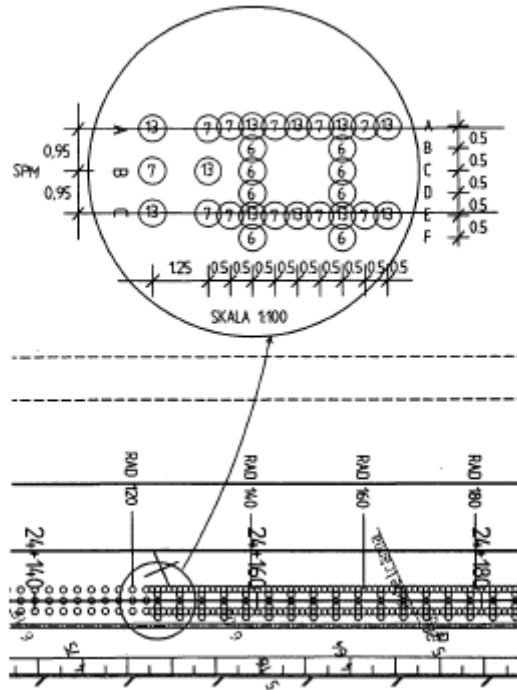


Figure 21: Panel installation pattern for vibration mitigation caused by high speed train at the Ledsgård, Gothenburg, Sweden (Holm et al, 2002)



Figure 22: Vibration mitigation using Dry deep mixing method; column installation in progress while commuter train passing (Holm et al, 2002)



Figure 23: Liquefaction mitigation along river bank at Napa Yatch club, California (Porbaha et al, 1999)

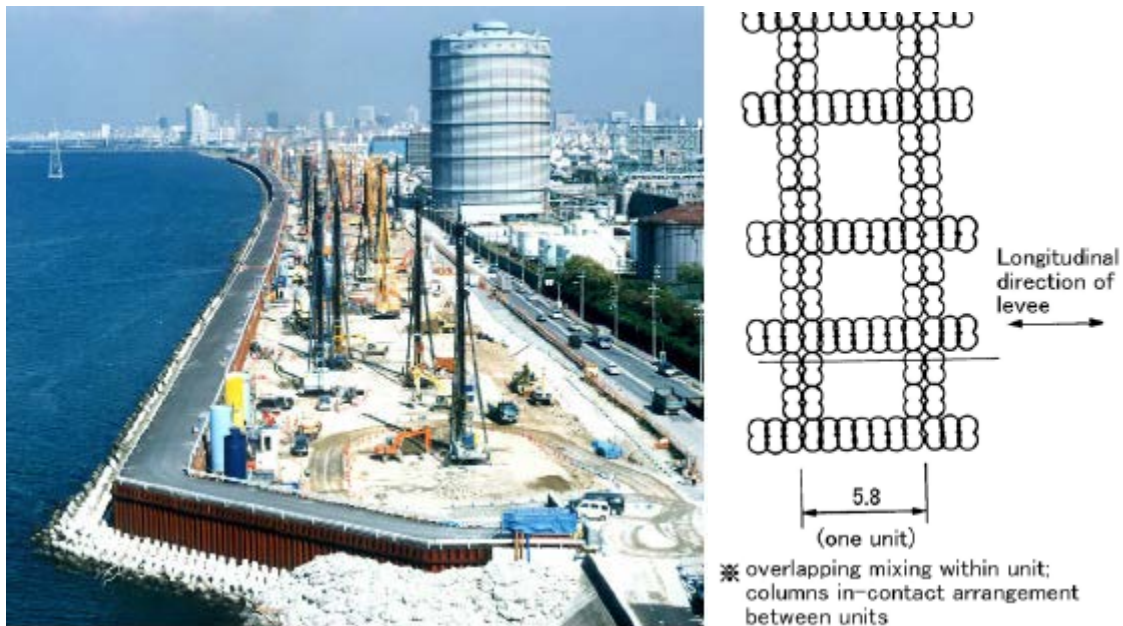


Figure 24: Application of DJM and resulting columns at Yodogawa river embankment in Japan (Yasui and Yokozawa, 2005)

3.1.4 Mass Stabilization

Mass stabilization is a shallow to deep stabilization method in which the entire volume of soft soil can be stabilized to a prescribed depth (Figure 26). The technique is relatively new and is highly suited for the stabilization of high moisture content such as clay, silty, organic soils and contaminated sediments (EuroSoilStab, 2002; Hayward Baker Inc). Mass stabilization offers a cost effective solution to ground improvement in site

remediation especially with a huge amount of contaminants and high water content. Remediation of most deposits of contaminated dredged sediments, organic soils and waste sludge usually make use mass stabilization method (Keller, 32-01E). The method provides an alternative to traditional method of soil improvement such as removal and replaces techniques.

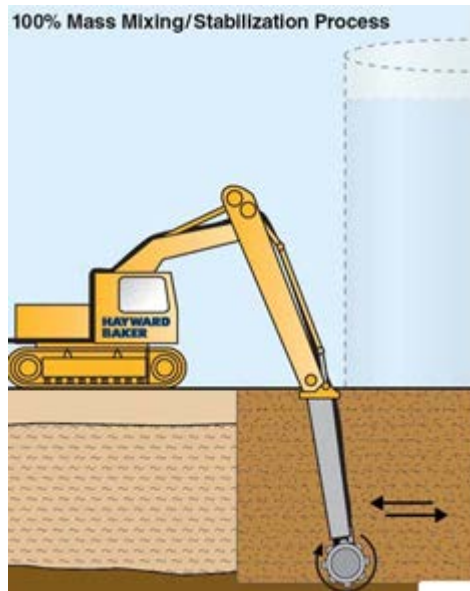
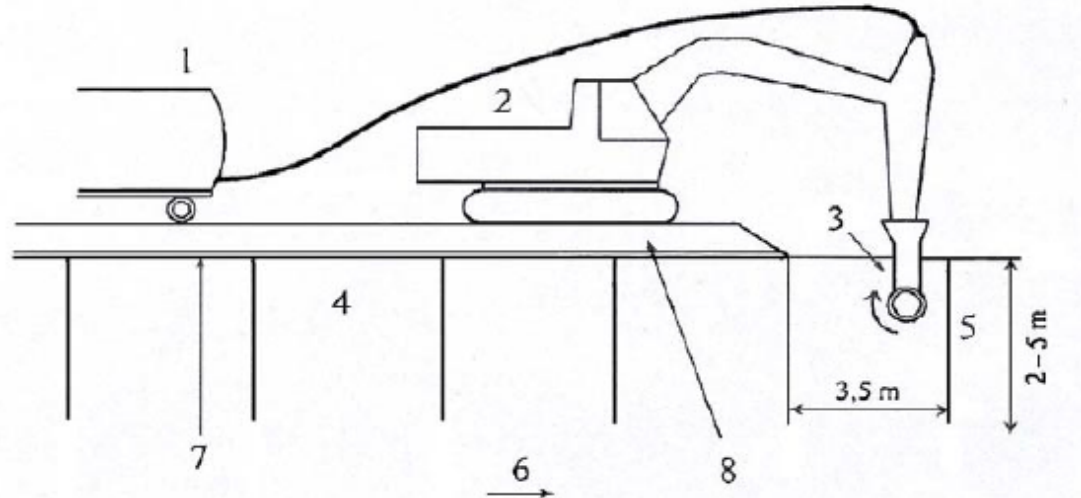


Figure 25: Mass mixing stabilization (Courtesy of ©Hayward Baker Inc)

The blending of the soil mass may be achieved by either use of excavator mounted mixing tool with unique shuttles pneumatically delivering the binder to the head of the mixing tool and into the mix zone (Figure 29) or by self-injection of binder into a rotating auger or mixing head and the soil (Figure 28). The mixer rotates and simultaneously moves vertically and horizontally while mixing the soil block. The diameter of mixing tool normally lies between 600 mm to 800 mm, with rotation speed between 80 and 100 rpm. Usually, the soil is stabilized in a sequence of a block which is defined as the operating range of the machine. The typical range correspond to 8 to 10 m² in plan and 1.5 to 3 m in depth (i.e. 2 m wide x 5 m long x 3 m deep) with production rate between 200 and 300 m³ of stabilized soft soil per shift (Figure 27). The amount of binder is typically in the range of 200 to 400 kg/m³ (EuroSoilStab, 2002).



Key features: 1. Stabilizer tank and scales; 2. Execution machine; 3. Mixing tools 4. Stabilized mass of soft soil; 5. Unstabilized soft soil; 6. Direction of mass stabilization; 7. Geotextile (Reinforcement); 8. Preloading embankment

Figure 26: Schematic diagram of mass stabilization (Massarsch and Topolnicki, 2005; EuroSoilStab, 2002)

In Nordic countries the amount of binder is in a typical range of 150 and 250 kg/m³, and the targeted shear strength is 50 kPa (Massarsch and Topolnicki, 2005). The method has advanced to include use of rapid cement as a binder in stabilization of contaminated dredged material at Port Hamina and shoreline of Helsinki, Finland, where stabilized contaminated dredged materials deposited between embankments created new areas (Andersson et al, 2001). Prior to initial set of the stabilized mass, a geo-membrane separator have to be placed on top of stabilized soil on which a selected granular base course material lies. These fill materials compresses the freshly stabilized mass forcing out all air pocket that may have formed during mixing (Hayward Baker Inc; Massarsch and Topolnicki, 2005; EuroSoilStab, 2002). According to EuroSoilStab (2002), deep stabilization method compared to other methods of stabilization (Figure 30) has the following main advantages:

- economic and flexible
- saving of materials and energy
- rapidity in improved engineering properties of the soil
- can be flexible linked with other structures and with the surroundings (no harmful settlement differences)



Figure 27: Dry mass soil mixing to strengthen soft soils beneath a planned roadway expansion at U.S. Highway 1, Key Largo, Florida (Hayward Baker Inc). Geo-fabric separate placed on top of stabilized mass before the selected base coarse layer is placed.

3.2 Ex-Situ Stabilization

The technology involves dislodging of the soils and or sediments from the original position and moves to other place for the purpose of amendment. These can be encountered in dredging of river channel and Ports. The main objectives of dredging can be either for amending the contaminated sediments to reduce toxicity and mobility or to maintain or deepen navigation channels for the safe passage of ships and boats (US EPA, 2004). Offsite treatment of the sediment can be done in confined disposal facilities (CDF) and then be used or disposed at designated site. Method of removal, means of transportation, availability of treatment location, disposal site or demand for reuse is key factors to consider when planning for ex-situ stabilization (Miller and Miller, 2007; PIANC, 2009). Treatment of sediments in CDF falls under ex-situ mass stabilization method, which can be accomplished in several ways depending on natural of sediments and water contents (Figure 31).



Figure 28: Mass stabilization with dry soil mixing of soft wet organics to control settlement for storage tanks at Port Everglades, Florida (Haward Baker Inc.)



Figure 29: Ex-situ for on-site use stabilization (mixing in place of contaminated dredged materials) (Wiki, unpublished document)

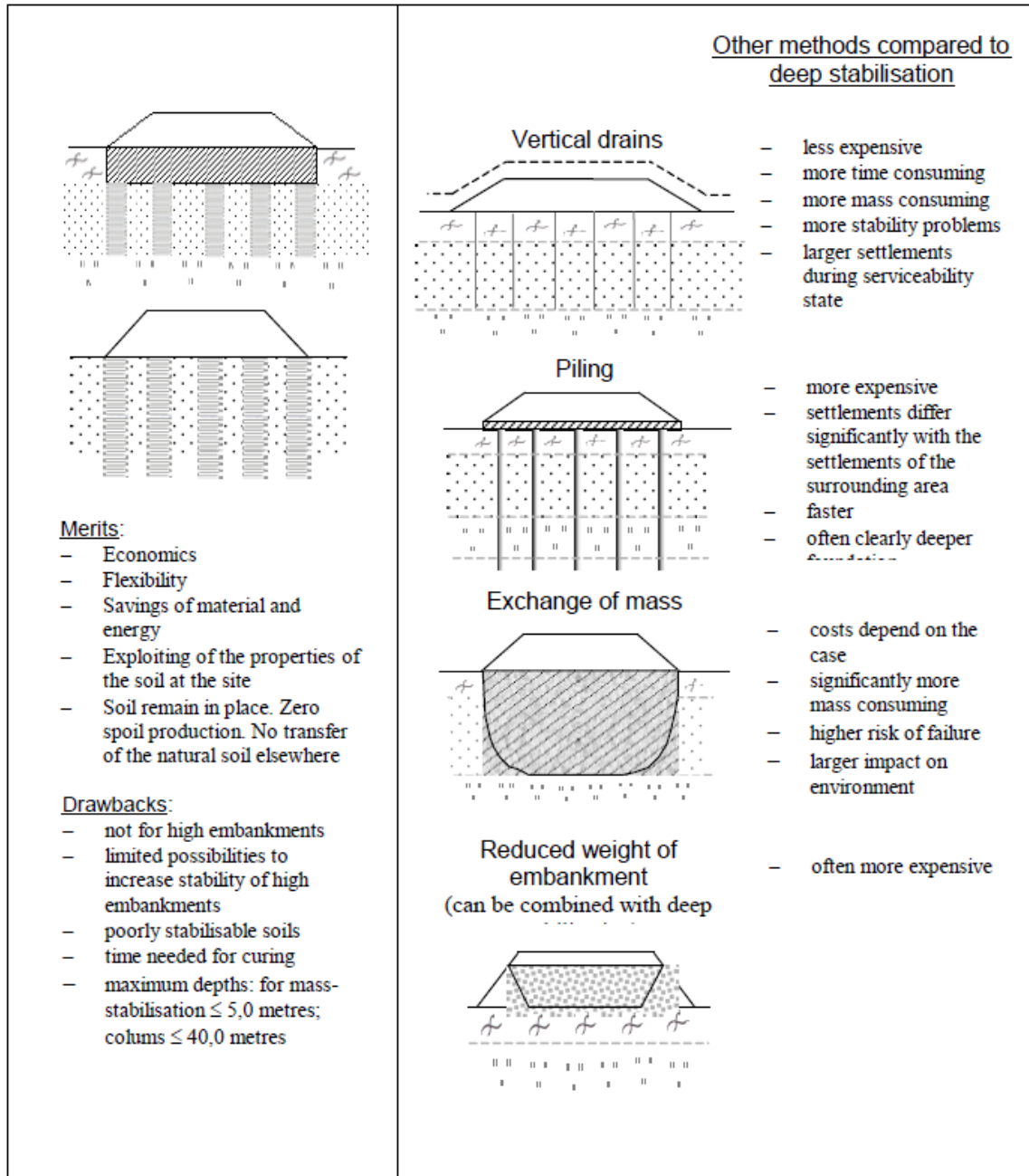


Figure 30: Comparison between deep stabilization method and other methods (EuroSoilStab, 2002)

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