CHAPTER 11

Deep Mixing Method

Equipment and Field of Applications

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11.1 INTRODUCTION

Ground improvement is a large and important domain in soil mechanics and geotechnical engineering and consists in a wide variety of techniques and methods adapted to a broad range of problems. It cannot be denied that during the past decades the importance of the ground improvement market has increased enormously. New methods, tools, and procedures have been developed and applied in practice. This is especially the case for the deep mixing method. This is not surprising, because it is an outstanding, competitive, and sustainable construction process.

For several decades, the deep mixing method has been used as a ground improvement technique. Although it was first used in the 1950s, the method was not largely employed in the United States until the 1980s. It was introduced in the 1960s in Japan and in the Scandinavian countries. In Europe, initially considered as an alternative to the jet grouting application, the deep mixing method was first used in the late 1980s with the emergence of various execution systems. After the development of various shaft configurations, the market witnessed the emergence of global mass stabilization, trench mixing (in the early 1990s), and the cutter soil mix (CSM) (2003). The historical development of the deep mixing method throughout the world is fully described in Bruce et al. (1998) and Topolnicki (2004). Kitazume and Terashi (2013) and Bruce (2014) respectively concentrate on the historical review of the method in Japan and in the United States.

According to the classification of the ground improvement methods adopted by the ISSMGE TC211 (see Chu et al., 2009), the deep mixing method can be classified as a ground improvement method with grouting-type admixtures. In this method, the weak soil is treated by mixing it with cement, lime, or other binders in situ using a mixing machine. In

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Table 11.1 Deep mixing terminology

CCP: chemical churning pile
CDM: cement deep mixing
CMC: clay mixing consolidation method
DCCM: deep cement continuous method
DCM: deep chemical mixing
DJM: dry jet mixing
DLM: deep lime mixing
DMM: deep mixing method
DSM: deep soil mixing
DeMIC: deep mixing improvement by cement stabilizer
In situ soil mixing
JACSMAN: jet and churning system management
Lime–cement columns
Mixed-in-place piles
RM: rectangular mixing method
Soil–cement columns
SMW: soil mix wall
SWING: spreadable WING method

Source: Porbaha (1998).

response to the growing variety of systems available on the market, Porbaha (1998) proposed a general terminology, as presented in Table 11.1.

Many reviews of the deep mixing method are available, including those by Terashi (2003), Topolnicki (2004), Larsson (2005), Essler and Kitazume (2008), Denies and Van Lysebetten (2012a), and Kitazume and Terashi (2013). Specialty international conferences have been held in Tokyo (1996 and 2002), Stockholm (1999 and 2005), Helsinki (2000), New Orleans (2003 and 2012), and Osaka (2009), with high attendance demonstrating the large worldwide success of this method.

In parallel, the results of national and European research programs have been published in multiple interesting reports (e.g., Coastal Development Institute Tokyo (CDIT), 2002; EuroSoilStab, 2002). The European standard for the execution of deep mixing, "Execution of Special Geotechnical Works—Deep Mixing" (EN 14679), was published in 2005, and in 2013 the U.S. Federal Highway Administration (FHWA) published a design manual titled "Deep Mixing for Embankment and Foundation Support." Currently, in its catalog of technologies, the web database Geotech Tools (Iowa State University, 2010–2014) provides practical guidelines for the design, execution, and control of the deep mixing works.

Most of these research projects and documents have focused on the global stabilization of soft cohesive soils such as silt, clay, and peat. Nevertheless, as illustrated in this chapter, the applicability of the method for structural applications can be no more put in doubt.

11.2 CONSTRUCTION PRINCIPLES AND EQUIPMENT

11.2.1 Introduction and classification

In the deep mixing process, the ground is mechanically (and possibly hydraulically or pneumatically) mixed in place while a binder, generally based on cement or lime, is injected with a specially made (or customized) machine. The deep mixing method can be classified according to its execution process based on the mixing method and the injection mode.

There are two types of installation methods based on the way the binder is injected into the ground (with or without water addition): the wet and the dry mixing methods. In the wet mixing method, which is more frequently applied, a mixture of a binder and water with possibly sand or additives is injected and mixed in place with the soil. Depending on the type of soil and binder, a mortar-like mixture is created that hardens during the hydration process (Essler and Kitazume, 2008).

In the dry soil mixing process, the binder is directly mixed with the soil (generally during the withdrawn phase). The binding agents directly react with the prevailing soil and the contained water and form a soil mortar. Quasthoff (2012) provides a brief state of the art in dry soil mixing and reviews its construction principles, its equipment, and its field of applications. Interested readers can also refer to the proceedings of the International Conference on Dry Mix Methods for Deep Soil Stabilization held in Stockholm in 1999 (Bredenberg et al., 1999).

As previously mentioned, the different types of soil mix systems available on the market can be classified according to the way the mixing is performed into the ground. Such classification has been provided in the past by Bruce et al. (1998), Topolnicki (2004), and Essler and Kitazume (2008). During the short courses of the last International Symposium on Ground Improvement IS-GI 2012 held in Brussels (see Denies and Huybrechts, 2012), Topolnicki (2012) presented an updated classification scheme as illustrated in Fig. 11.1. The different systems are separated according to four levels of classification taking into account (1) the dry or wet mixing; (2) the mechanical, hydraulic, or hybrid method of mixing; (3) the position of the mixing; and (4) the axis of rotation of the mixing tools.

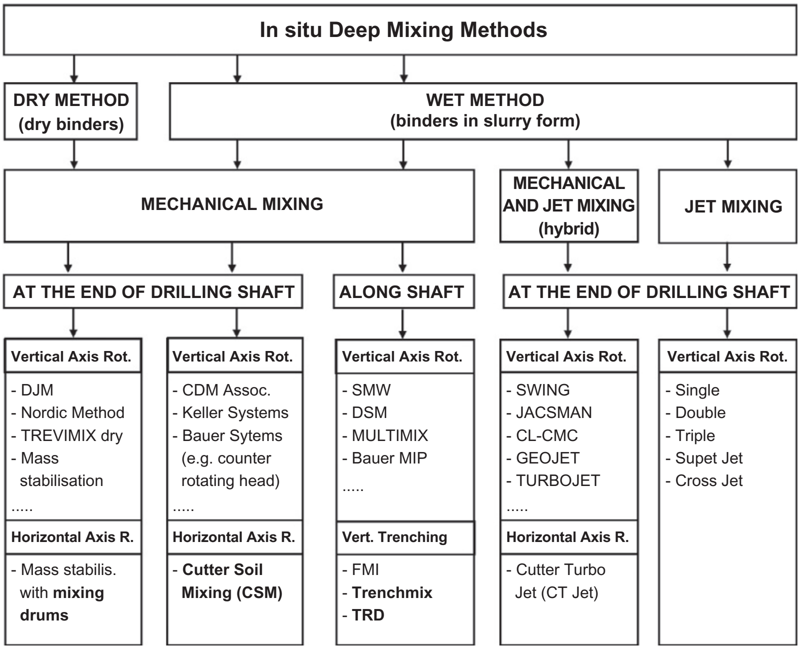


Figure 11.1 Updated classification scheme of soil mixing systems. *(Source: From Topolnicki (2012)).*

Depending on the application, different improvement patterns can be designed with these various systems considering soil–cement columns, rectangular soil mix panels, continuous barriers, or global mass stabilization such as illustrated in Fig. 11.2. Typical improvement patterns of treated soil mass can be found in CDIT (2002), Topolnicki (2004), FHWA (2013), and Kitazume and Terashi (2013).

The deep mixing method can be performed on land or for marine applications. Kitazume and Terashi (2013) describe the equipment available for

Figure 11.2 Typical ground improvement patterns of treated soil (soil–cement columns, soil mix panels, continuous barriers, and global mass stabilization).

Table 11.2 Deep mixing methods and equipment used internationally

Reference	Methods and equipment
Bruce et al. (1999)	DJM, lime–cement columns, Trevimix Dry
CDIT (2002)	CDM, DJM
Topolnicki (2004)	DJM, Nordic method, Trevimix Dry, shallow soil mixing (SSM) method, CDM, DCM, SCC, Hayward Baker–Keller mixing tools, Bauer mixing tools, mix-in-place (MIP), SMW, DSM, Colmix, spread wing (SWING), JACSMAN, Hydramech, Trevimix Wet, Turbojet, Geojet, FMI (cut–mix–injection) machine
Larsson (2005)	CDM, Colmix, CSM, TRD, Hayward Baker–Keller mixing tools, SCC, Geo-Solutions tools, Raito tools, Schnabel DMW (deep mix wall), May Gurney tools, Trevi tools, Rectangular 1 (cutting wheels), Rectangular 2 (box columns), FMI (cut–mix–injection) machine, DJM, Nordic method, SSM method, ALLU mass stabilization mixing tools, SWING, JACSMAN, LDis
Kitazume and Terashi (2013)	CDM, DJM
FHWA (2013)	CDM, DJM, DSM, SMW, Trevimix Wet, Colmix, soil removal technique, SSM, ISS auger method, RAS column method, Rectangular 1 (cutting wheels), Rectangular 2 (box columns), SAM, cementation, single axis tooling, rotomix, CSM method, SWING, JACSMAN, LDis, GeoJetTM, Hydramech, RAS Jet, Turbomix/Turbojet, TRD, Nordic method, Trevimix Dry, MDM (modified deep mixing), dry soil mixing mass, Schnabel DMW (deep mix wall)

near-shore construction, such as port and harbor facilities or man-made island constructions, including the use of deep mixing barges.

Table 11.2 provides a list of references detailing various soil mixing equipment used internationally. Bruce et al. (1999) especially provide a summary of the mixing equipment for the common dry deep mixing methods. Topolnicki (2004) and Larsson (2005) provide a full description of the soil mixing systems used in Europe, Japan, and the United States. Kitazume and Terashi (2013) mainly focus on the application of the cement deep mixing (CDM) and dry jet mixing (DJM) techniques as applied in Japan. FHWA (2013) contains tables detailing deep mixing equipment, tooling data, and treated soil material properties.

The following sections do not provide an exhaustive review of the aforementioned deep mixing systems. Rather, they illustrate the variety of the wet deep mixing equipment available on the market today. Dry methods and shallow mixing methods are not discussed here.

11.2.2 Wet mixing in single or multiple shaft configurations

A large variety of wet mixing systems are available in single shaft configuration. In these soil–cement column systems, the mixing can be mechanically performed at the end of the shaft, such as illustrated in Figs. 11.3 and 11.4, or alternatively along the shaft. In several circumstances, hybrid mixing can be applied with jet assistance, such as in the tubular soil mixing (TSM) system. The TSM technique, as used in Belgium by Smet-Boring, uses both mechanical and hydraulic methods of mixing. Apart from the rotating mixing tool, the soil is cut by the high-pressure injection (up to 500 bar) of the water/binder mixture. As illustrated in Fig. 11.5, an external tube can be used to obtain regular diameter.

To increase production rate, multiple shaft configuration systems have been developed, some of which are equipped with a jet assistance device (Larsson, 2005).

Figure 11.3 Keller wet mixing system in single shaft configuration (available tool diameter for single shaft ranging between 40 and 240 cm). *(Source: From Topolnicki (2012), with courtesy of Keller).*

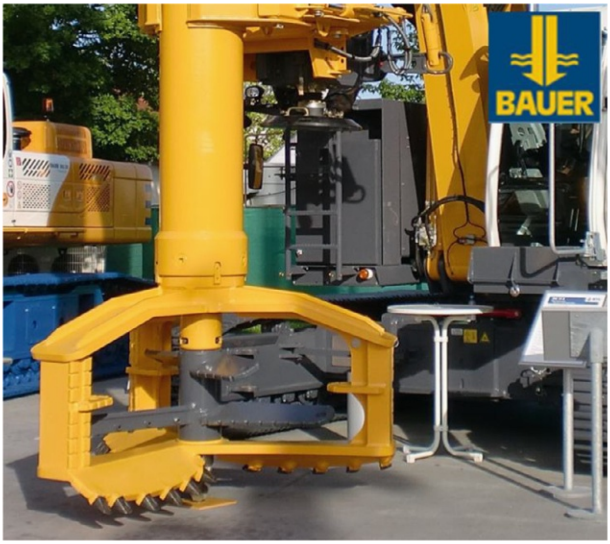


Figure 11.4 Bauer Single Column Mixing-Double Head, SCM-DH system (available tool diameter for single shaft ranging between 180 and 240 cm). *(Source: After Topolnicki (2012), with courtesy of Bauer).*

Figure 11.5 Smet Tubular Soil Mixing TSM system (column diameter of 38–73 cm). *(Source: After Denies et al. (2012a) and Topolnicki (2012), with courtesy of Smet-Boring nv).*

11.2.3 Wet mixing spreadable systems

Soletanche Bachy has developed the "Springsol" wet soil mixing tool (Guimond-Barrett et al., 2012). As illustrated in Fig. 11.6, this tool is equipped with two mixing blades that spread out under the action of springs. In its folded configuration, the tool diameter is 160 mm, enabling its

Figure 11.6 Soletanche Bachy wet spreadable mixing tool SPRINGSOL. *(Source: From Borel (2012) and Guimond-Barrett et al. (2012), with courtesy of Soletanche Bachy).*

insertion into a temporary casing. By increasing the length of the mixing blades, the column diameter can be adapted (e.g., 40 and 60 cm as illustrated in the top right side of Fig. 11.6). The main advantages of the Springsol tool are the ability to reinforce the ground under an existing railway track or an existing platform (slab and superficial isolated or continuous footings) and the ability to work under low headroom conditions (Borel, 2012). Keller has also developed wet spreadable systems. The first spreadable tool designed by Keller had an external diameter of 300 mm (for its core retractable tool). Keller Foundations has designed the FLAPWINGS system. It consists of a 150-mm core retractable tool that is able to open in order to perform soil mix columns with a diameter of 600 mm (Lambert et al., 2012).

11.2.4 CSM panels

The execution of soil mix rectangular panels can easily be performed using the cutter soil mixing (CSM) system developed by Bauer Maschinen GmbH. As reported in Gerressen and Vohs (2012), the CSM is based on the principle of the trench cutter technique. It is used mainly for the construction of cutoff walls, earth retaining structures, and ground improvement. As it is derived from Bauer Cutter technology, the system extends the applicability of soil mixing to much harder strata. While a self-hardening water/binder mixture is being introduced, soil formations are easily penetrated, broken down, and mixed with the water/binder mixture using the cutter wheels as cutting and mixing tools. The two cutting wheels rotate independently about a horizontal axis. Figure 11.7 illustrates the cutting and mixing tools of the CSM developed by Bauer. Another CSM system that is available on the market has been developed by Soletanche Bachy-TEC (Borel, 2012).

11.2.5 Trench mixing

The principle of the trench mixing method is to produce a soil mix barrier, generally up to a depth of 10 m, in a single continuous pass, which is an advantage particularly in the case of water retaining function (no joints). Figure 11.8 shows the Trenchmix system. For deep and large applications, use of the trench remixing deep (TRD) system can also be envisaged (Burke, 2009).

11.2.6 Advantages and disadvantages of the deep mixing method

The variety of deep mixing equipment used internationally allows the execution of soil mix material in a large range of soil types. Table 11.3 summarizes the main advantages and limitations of the method, as given in Topolnicki (2012). According to the author's experience, the following are additional advantages of the deep mixing method:

Figure 11.7 The cutting/mixing tools of the Bauer CSM system (left) and the QuattroCutter and SideCutter systems (right). *(Source: From Gerressen (2012), with courtesy of Bauer).*

Figure 11.8 Trenchmix tool. *(Source: Courtesy of Soletanche-Bachy/Mastenbroek).*

Table 11.3 Advantages and disadvantages of the deep mixing method

Advantages	Disadvantages
High productivity usually possible, hence economical for large-scale projects	Depth limitations (depending on the method applied)
Can be potentially used in all types of soils and fills (without obstructions)	Not applicable in soils that are very dense, very stiff, or that may have boulders
Column's spacing and patterns highly variable, arrangements tailored to specific needs	Limited or no ability to install inclined columns (depending on the equipment applied)
Engineering properties of treated soil can be closely designed	Uniformity and quality of mixed soil may vary considerably in certain conditions
Causes minimal lateral or vertical stress that could potentially damage adjacent structures	Columns cannot be installed in close proximity to existing structures (except hybrid mixing)
No vibration, medium-low noise	Freeze/thaw degradation may occur
Very low spoil (especially for dry method)	Significant spoil produced with wet method
Can be used for on-land, waterfront, and marine projects	Weight of the equipment may be problematic for weak soils (depending on the method)
Quality of treatment verifiable during construction	Limited ability to treat isolated strata at depth

Source: Topolnicki (2012).

- Use of the existing soil as a construction material.
- Control of the geometry of the soil mix element with depth.
- Contrary to concrete secant pile walls, the execution of the soil mix walls does not suffer from delayed supply (e.g., due to traffic jams) of the fresh concrete
- For the wet mixing method, the amount of spoil return is more limited and more controllable than that for jet grouting or slurry walls.
- Dewatering is not required.

11.2.7 Wet or dry mixing method

The choice of using dry or wet mixing methods is often related to the local historical developments. It can also be linked to the available machines on the local market or to economics. Other aspects may also have to be considered. Topolnicki (2012) compared both processes in Table 11.4.

Table 11.4 Choice of the dry or wet process

Item of concern	Main limitations
Initial water content of the soil to be treated	Cohesive soils with moisture content $w=60$–200% are best suited for the dry process (lower limit $w>20\%$, water content below plastic limit is not fully available for hydration).
Quality of mixing	Wet process usually provides better homogeneity of stabilized soil because of easier distribution of slurry across the column area, prehydration of cement, and longer mixing time.
Compressive strength of soil–binder mix	Higher strength is more reliably obtained with the wet process, except for very wet soils.
Ability to penetrate through hard soil layers	Much higher for the wet process due to the "lubrication" effect of the injected slurry and due to higher torque capacity of rigs.
Stratified soils	Wet mixing can provide more uniform strength along the column length due to partial soil exchange/movement in the vertical profile; quality control more difficult for the dry process.
Spoil	Dry mixing creates very little or no spoil.
Use of combined binders and industrial by-products	Quite frequent in dry mixing, slag cement in wet mixing, other binders and by-products very rare.
Air temperature below 0 °C	Dry process is significantly less affected by low temperatures because compressed air is used to transport the binder.
Column reinforcement	Possible in combination with the wet process.

Source: Topolnicki (2012).

11.3 HYDROMECHANICAL CHARACTERIZATION OF THE DEEP SOIL MIX MATERIAL

Several parameters have an influence on the produced deep soil mix material. The quality of the soil mix material depends on the binder type and content, the in situ soil, the execution process, and the curing conditions. The contaminated character of the ground and the exposure conditions of the soil mix elements during their lifetime will have a direct impact on the durability of the soil mix material. Design criteria of permanent soil mix elements may be based on the execution monitoring (of the mixing energy, depth, etc.) and on performance tests, including unconfined compressive strength (UCS), freeze–thaw and wet–dry durability, leachability (in particular cases), porosity, and permeability (if required) tests. Nevertheless, it must be kept in mind that the test procedures directly influence the results of the characterization, possibly resulting in various conclusions.

The topic of mechanical characterization of the soil mix material is beyond the scope of this book. The reader can refer to the following references to obtain information relative to this subject: Bruce et al. (1998), Porbaha et al. (2000), CDIT (2002), Topolnicki (2004), Kitazume (2005), Denies et al. (2012b), Denies and Van Lysebetten (2012a, 2012b), Kitazume and Terashi (2013), FHWA (2013), and, specifically for the dry mixing method, Bruce et al. (1999) and Bredenberg et al. (1999).

11.4 FIELD OF APPLICATIONS AND CASE HISTORIES

Originally, the deep mixing method was developed for ground improvement applications in soft clays and organic soils. Nevertheless, recently, it is increasingly more dedicated to various structural and environmental applications. Table 11.5 summarizes the main applications of the deep mixing method. The following sections illustrate most of them.

11.4.1 Deep mixing method for excavation support: Construction of earth and water retaining structures

In recent years, the deep mixing method has increasingly been used for the construction of earth–water retaining structures. In fact, the soil mix walls represent a more economical alternative to concrete secant pile walls and even, in several cases, king post walls (i.e., soldier pile walls). An historical background of excavation support using soil mix walls is proposed by Rutherford et al. (2005). In this application, the discrete soil mix elements (columns or panels) are placed next to each other, in a secant way. By overlapping the different soil mix elements, a continuous soil mix wall is realized. Steel H- or I-beams are inserted into the fresh soil mix material to resist the shear forces and bending moments. The maximum installation depth of these soil mix walls is on the order of 25 m, but higher installation depths may be observed in the future. The main structural difference between the soil mix walls and the traditional secant piles is the constitutive soil mix material instead of concrete.

Table 11.5 Summary of the deep mixing applications

Soil reinforcement and foundations
As an alternative to classical foundation
For underpinning with the help of the spreadable systems
For the realization of the foundation of linear structures such as railway tracks and pipelines with the help of the trench mixing systems
Earth/water retaining walls\
For excavation
As shaft structure
As pit for (micro)tunneling activities
Cutoff walls, floodwalls, and reinforcement of land levee and embankment
Slope stabilization and landslide mitigation
In situ remediation
For Permeable Reactive Barriers (PRB) walls
For containment walls
For soil treatment by stabilization/solidification
Global mass stabilization
For the total shallow treatment of an area (e.g., for industrial installations)
Liquefaction mitigation
With the construction of soil mix caissons
With specific arrangement of isolated soil mix elements and soil mix walls
Land reclamation
Particularly in the case of near-shore construction (port and harbor facilities and man-made islands)

In Belgium, the deep mixing method is mainly used for the construction of soil mix walls for earth and water retaining structures. Figure 11.9 illustrates different cases of excavation performed in Belgium with the help of anchored or shored CSM panels or soil–cement columns. The following two case histories illustrate the possibilities of this field of application.

Pinto et al. (2012) report a case history in Portugal for which the CSM technique was applied for the construction of two shafts with temporary earth and water retaining functions. The shafts, approximately 18 m deep and 15 m in diameter, were built to allow the installation of a water supply pipe under a river using microtunneling technology. The CSM panels were built with an overall depth of 24 m and reinforced with steel beams (type IPE 300).

The CSM panels were designed to transmit horizontally the earth and water pressures to these vertical beams. The beams were braced at the top by a capping beam (made of reinforced concrete) and by three lower levels of steel ring beams, as illustrated in Fig. 11.10. For the design, a

Figure 11.9 Different types of soil mix wall with a retaining function.

two-dimensional finite Element modeling (FEM) axisymmetric model was adopted using Plaxis software.

Pinto et al. (2012) also reported on the execution of an earth–water retaining and foundation structure (with permanent function) realized for the construction of a pumping station. The depth of the excavation was 12 m. CSM panels with an overall depth of approximately 24 m were performed and reinforced with vertical steel beams (type IPE 300) in order to resist the structural loads, earth and water pressures, and to limit the deformations. Buttress panels were also built in order to increase the overall stiffness of the earth retaining structure, as illustrated in Fig. 11.11. The CSM panels were designed to be integrated with the final foundation and earth retaining solution and to limit the water inflow into the excavation. For the design, two-dimensional FEM analyses were again carried out using Plaxis software.

This second case history provides an excellent introduction for the following field of application of the method: the use of the deep mixing method as an alternative to the traditional foundation solutions.

11.4.2 Deep mixing method for foundation applications

Although the deep mixing method has been used for several decades as a ground improvement method, there is a growing trend: the use of soil mix elements with a bearing function. This practice is illustrated with a case

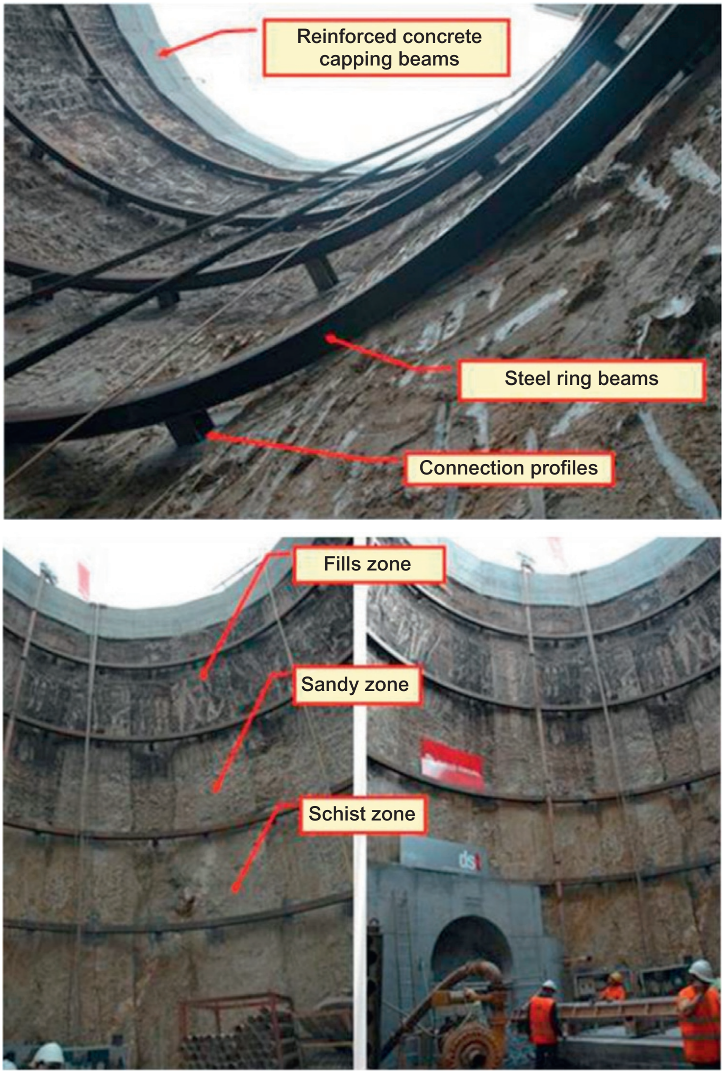


Figure 11.10 Inside view of the shaft after excavation. *(Source: After Pinto et al. (2012))*.

history reporting the use of CSM panels as the foundation of an industrial building in Portugal.

Peixoto et al. (2012) describe an application of the CSM technology for the foundation of an industrial building at Fréjus, France. The main concern during the design was the minimization of the total and differential settlements of the building structure. The loads were transmitted to the

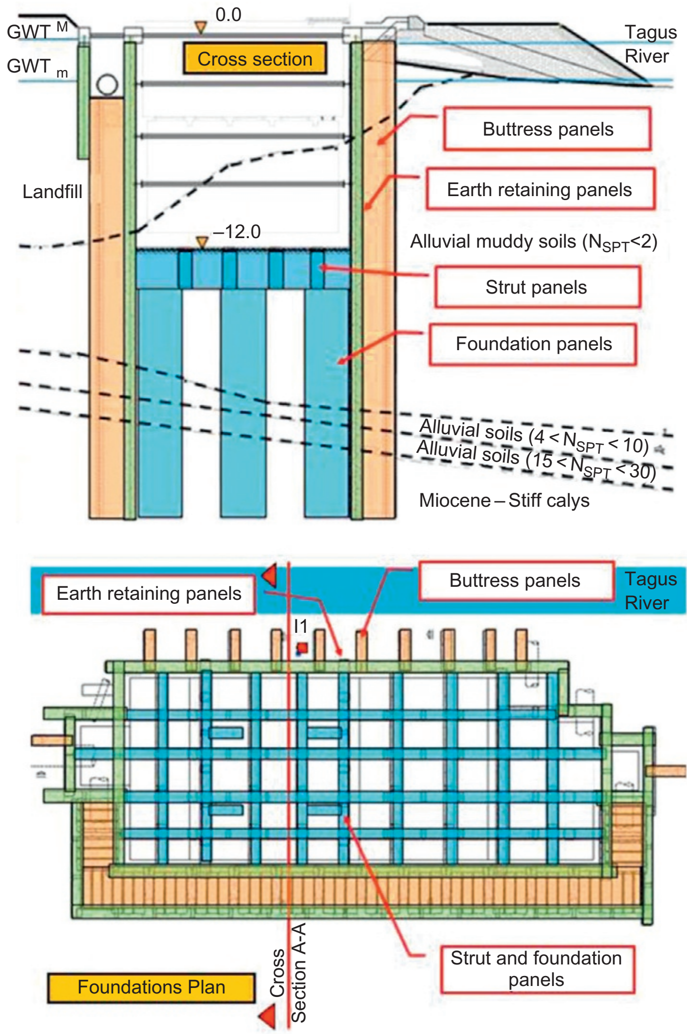


Figure 11.11 Cross section (top) and plan of the adopted solution (bottom). *(Source: After Pinto et al. (2012)).*

marl–sandstone substrate, detected at a depth varying between 3 and 7 m. As illustrated in Fig. 11.12a, enlargement of the top of the panels was also executed to ensure an efficient transfer of the load to the CSM panels. The panel caps were filled by the overflow mixture resulting from the execution of the CSM panels. Figure 11.12b presents the distribution of the CSM panels. A load transfer layer made of granular material and with a thickness of 0.60 m was finally constructed, on which the concrete bottom slab of the building

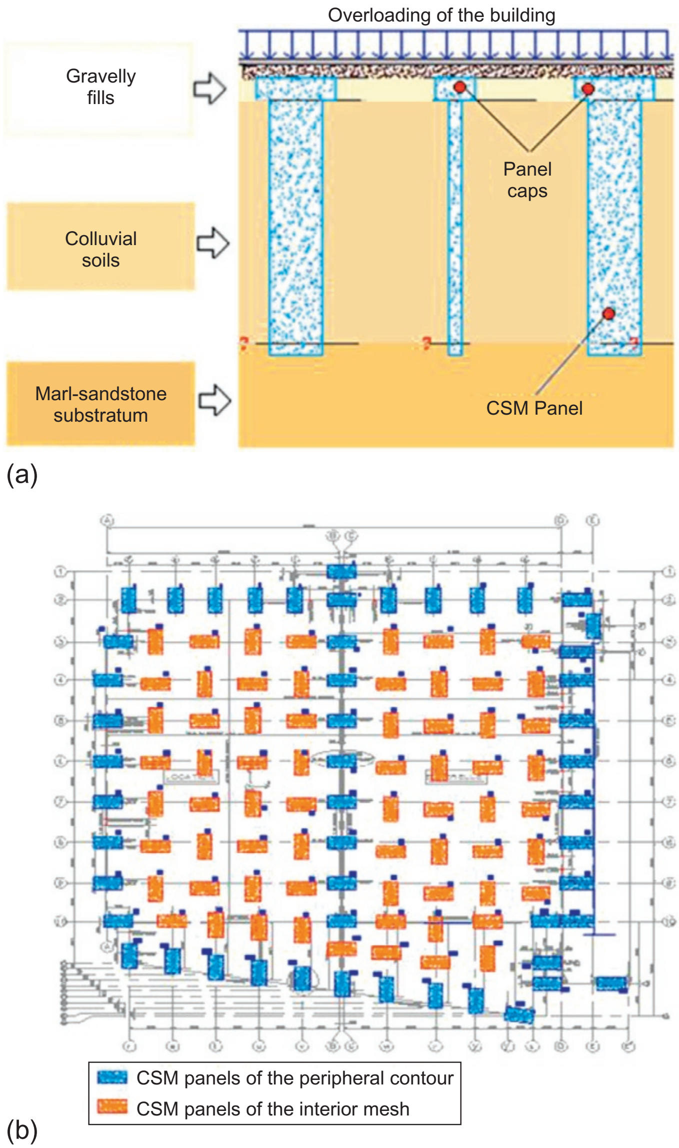


Figure 11.12 (a) Cross section of the performed solution and (b) plan view of the CSM panel distribution. *(Source: From Peixoto et al. (2012)).*

was placed. The analysis of the solution in terms of long-term settlements was carried out using the FEM Plaxis program.

This case study is a reflection of a current growing trend: the comparison during the design phase between at least two alternative solutions—the design of the foundation with the help of a classical pile (or pile raft) solution and the possibility to use soil mix elements covered by a load transfer platform made of granular material (possibly) reinforced with geosynthetics. Although there are many standards and guidelines available for the design of pile foundation, the use of numerical modeling to assess the safety of the combined solution (soil mix elements and load transfer platform) is usually required because of the lack of knowledge of the fundamental mechanisms governing the behavior of this solution.

When considering the long-term structural function of these soil mix elements, the durability of the soil mix material has to be discussed. As reported by Denies et al. (2015b), durability of the soil mix material is a complex topic because it relates to aspects of the evolution and/or the degradation of the hydromechanical characteristics of the soil mix material with time (strength, stiffness, permeability, pH, etc.).

However, there is also the issue of the durability of the soil mix material executed in contaminated grounds or in soils containing compounds that can have a negative effect on the development of its characteristics (chlorides, sulfates, hydrocarbons, heavy metals, etc.). The durability of the soil mix material will also have an impact on the (rate of) corrosion of steel beams integrated into the fresh soil mix material during execution. In the soil mixing process, the contaminants are directly mixed with the injected binder and with the ground. Hence, they will be integrated into the soil mix matrix. As a result, the potential impact of these compounds is more important for the soil mix elements than for cast-in-place or precast concrete elements.

As reported by Denies et al. (2015b), two antagonistic phenomena play a role in the durability of the soil mix material. On the one hand, there is a long-term increase in its strength with time (Terashi, 2002; Topolnicki, 2004; Ganne et al., 2010; Bellato et al., 2012; Filz et al., 2012). On the other hand, there is a progressive degradation of the material observed with time due to several factors (outward diffusion of the cations Ca^{2+}, carbonation process, and freeze–thaw and wet–dry cycles). In addition to these aging effects, designers and soil mix contractors have to consider the contaminated character of the construction site before the start of the works. Some contaminants can be harmful either for the soil mix material (binding and hardening processes) or for the steel beams installed in it (corrosion).

For temporary structural soil mix elements, the presence of the contaminants leads to question the efficiency of the binding and the hardening of the soil mix material. A preliminary study allows the identification and determination of the concentrations of the contaminants that may have a potential deleterious impact on the binding and hardening processes. In function of these concentrations, a preliminary laboratory test campaign may be performed to verify the efficiency of these processes in the presence of these contaminants and to determine the influence of the type and the content of cement.

For permanent structural applications, it is very important that the soil mix material continues to fulfill its function in the long term (arching effect to distribute the earth and water pressures between the steel beams, long-term permeability and bearing functions, etc.). In addition, and if relevant, the risk of corrosion has to be considered.

The short- and long-term terminology as well as the temporary or permanent character of the construction should be defined in the job specifications or in the future standards. For example, a soil mix wall used only during the time of excavation to support the earth pressure would ensure a temporary retaining function. On the other hand, soil mix elements ensuring a bearing function during the lifetime of a definitive construction (building, bridges, etc.) would be characterized as soil mix elements with a permanent bearing function.

11.4.3 Deep mixing method for support of land levees and floodwalls

Hurricane Katrina passed southeast of New Orleans on August 29, 2005. The storm caused more than 50 breaches in drainage canal levees and also in navigational canal levees, and it precipitated one of the worst engineering disasters in the history of the United States. In response, construction and reconstruction of levees were planned, in several cases using the deep mixing technique.

The LPV-111 project consisted of the raising of an existing 8.5-km levee, which rested on a foundation of soft organic clay. LPV-111 is part of the New Orleans East Back Levee, which is an essential component of the New Orleans Hurricane Protection System. The deep mixing method was selected to stabilize and support the burden of the new levee, as illustrated in Fig. 11.13. That project resulted in the production of more than 1,300,000 m^3 of soil mix material. A preliminary laboratory program (bench-scale test) and a field test program (validation tests) were conducted to estimate the appropriate binder type and dosage and equipment configuration capable to efficiently meet the technical requirements of the project. Leoni and Bertero (2012) give a general overview of the project and present the results of the bench-scale and validation test programs with a discussion

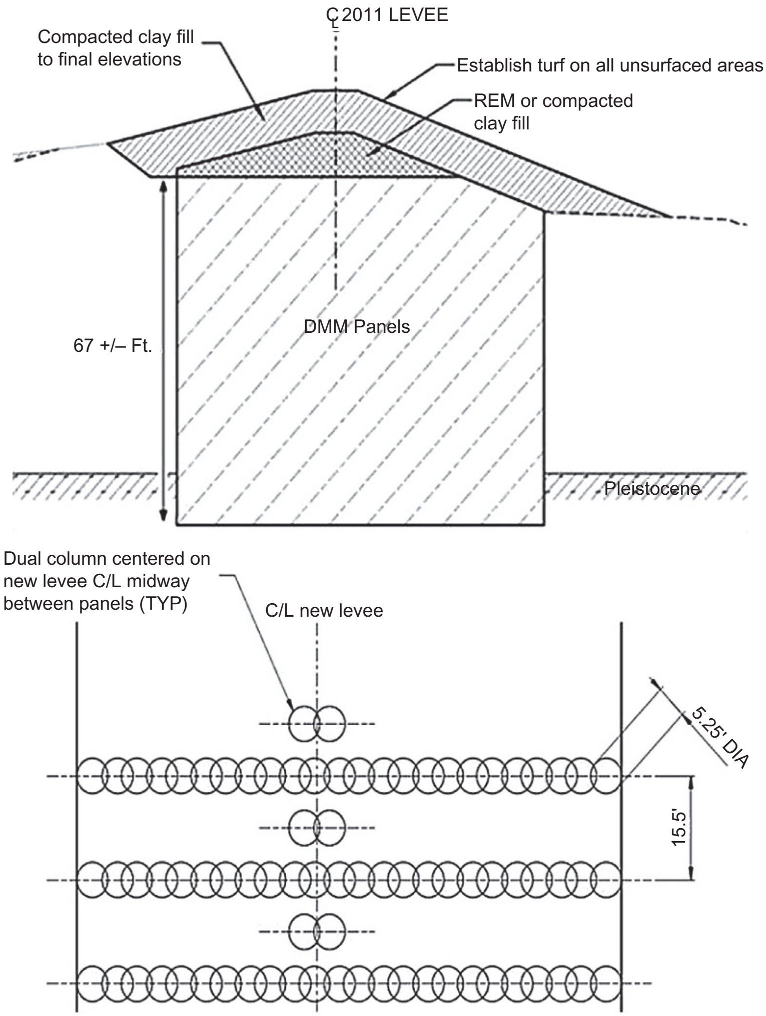


Figure 11.13 Typical design of deep mixing stabilization at LPV-111 (cross section and plan view). *(Source: After Leoni and Bertero (2012)).*

on the UCS design consideration based on the testing of 5000 core samples. At LPV-111, the contractor used two different deep mixing systems: the Trevi Turbo Mix, single and double, and the Contrivance Innovation Cement Mixing Columns.

In New Orleans, dry deep mixing was also used to improve the stability of a section of the land levee and floodwall along the Orleans Avenue Canal.

McGuire et al. (2012) studied the stability of this construction by using the finite difference method (using the FLAC program) and limit equilibrium analysis (using Spencer's method).

In these applications, the soil mix panels not only play the role of support for the embankment but also reinforce the global stability of the levee. For the design aspects related to the deep mixing for land levees and floodwalls, readers can refer to the keynote lecture of Filz et al. (2012) and to the design manual of the FHWA (2013).

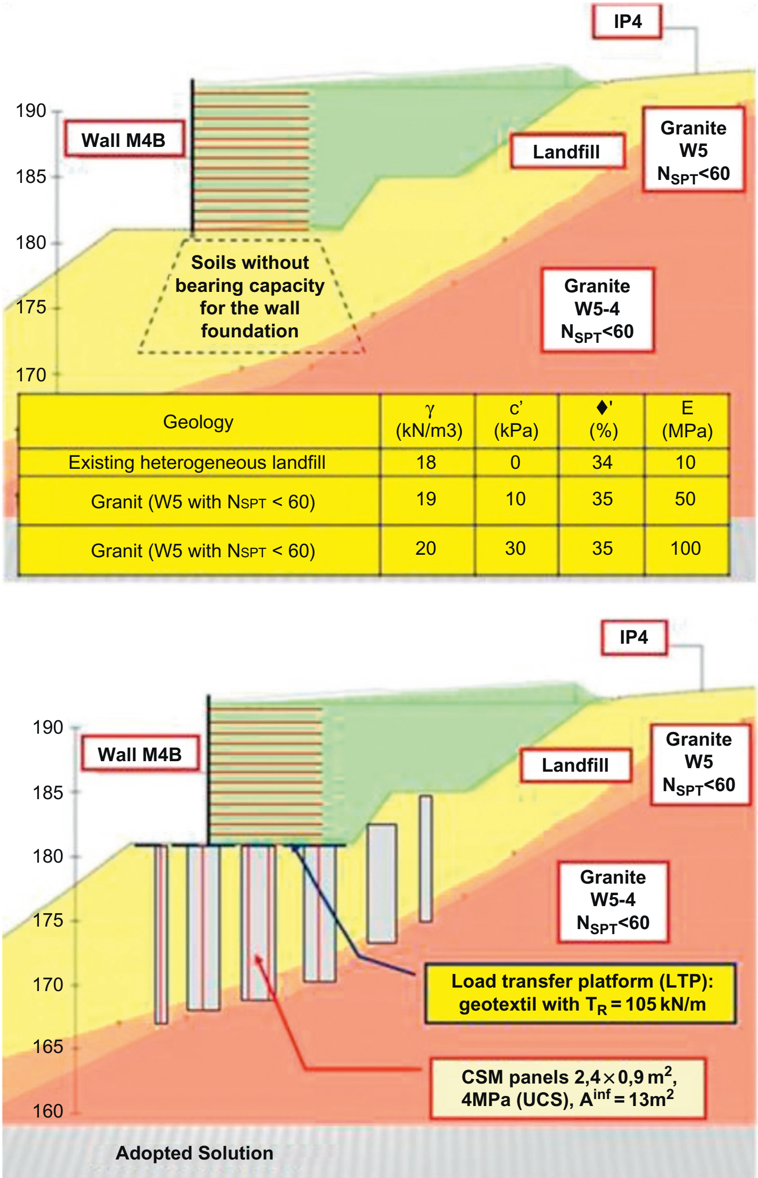
11.4.4 Deep mixing method for slope and landslide stabilization

This field of application is similar to the previous one. The stabilization of slope can be realized with the use of soil mix elements installed through its failure surface.

Pinto et al. (2012) describe the widening of an existing road platform (indicated by IP4 in Fig. 11.14) near the city of Amarante in Portugal. CSM panels were executed to stabilize a slope made of heterogeneous landfills that were used for the construction of the existing road platform. A cross section of the geological conditions and the adopted solution are illustrated in Fig. 11.14. CSM panels also serve as foundation for the reinforced fill (maximum height is approximately 20 m) and the motorway traffic with the aid of a load transfer platform. For the design, two-dimensional analyses were carried out using Slide and Plaxis software in order to evaluate the overall stability for static and seismic loads.

Before beginning deep mixing works, it is imperative to identify the potential failure surface of the slope to be stabilized. Moreover, as explained in McGuire et al. (2012), multiple modes of failure must be considered in the design.

Gaib et al. (2012) describe the use of CSM panels for the slope stabilization of the "Fountain Slide" in British Colombia. This slide has been active for decades, and it is part of a massive postglacial earthflow known as the Tunnel Earthflow. The estimated landslide volume is approximately 750,000 m^3. Twenty barrettes, approximately 8 m long and each composed of three individual CSM panels, were constructed with an orientation perpendicular to the slide. If in situ monitoring of the displacement shows a decrease in the movement rate, no global mitigation has been obtained with regard to the important volume of moving soil.



Geology	γ (kN/m3)	c' (kPa)	φ' (%)	E (MPa)
Existing heterogeneous landfill	18	0	34	10
Granit (W5 with N_{SPT} < 60)	19	10	35	50
Granit (W5 with N_{SPT} < 60)	20	30	35	100

Figure 11.14 Cross section of the geological conditions and adopted solution. *(Source: From Pinto et al. (2012))*.

11.4.5 Deep mixing method for cutoff walls

Soil mix walls or trenches can be used as seepage barriers to limit the flow of water (including or not contaminants). Figure 11.15 illustrates the installation of a cutoff wall in a dike body built in Aigle, Switzerland. The role of the dike is to protect industrial installations along the Rhone River against flooding. The core of the dike was realized in a continuous pass with the use of the Trenchmix method of Soletanche Bachy. In this case, the soil mix material has mainly a cutoff function. Its permeability is the key parameter of the design. Nevertheless, the soil mix material has to have sufficient strength to resist internal erosion due to the hydraulic gradient. It is also possible to combine different functions: the soil mix elements are then designed and built to improve the bearing capacity of the embankment, to improve its stability, and to ensure its cutoff function.

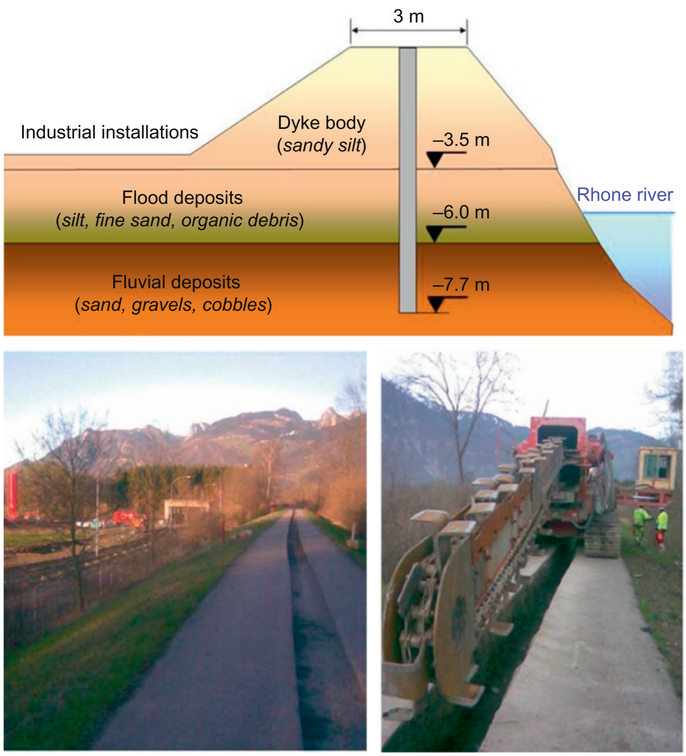


Figure 11.15 Reinforcement of a dike body with the help of the Trenchmix method. *(Source: From Borel (2012), with courtesy of Soletanche Bachy).*

11.4.6 Soil mixing remediation technology

As reported in Al-Tabbaa and Evans (2003), soil mixing was introduced in approximately 1995 in the United Kingdom for geoenvironmental applications, such as the containment of contaminants in and the remediation of brownfields. Since the beginning of the STARNET project in 2001, this field of application has undergone a major evolution.

The STARNET project (http://www-starnet.eng.cam.ac.uk) was established in May 2001 to promote the development of research work on and implementation of stabilization/solidification (S/S) treatment and remediation practices for the numerous brownfield areas present in the United Kingdom. Many references are available on the topic of soil mix remediation technology as reported in the seven "states of practice" reports of the STARNET project (Perera et al., 2005). As a result of the evolution of this application, the deep mixing is currently dedicated to

- the construction of cutoff containment walls;
- the construction of permeable reactive barriers (also called PRB walls); and
- the S/S treatments of the ground.

These are three applications for which permeability and leachability of the soil mix elements are essential parameters but strength often plays a secondary role.

As described in Al-Tabbaa et al. (2012), the permeable reactive barriers are installed in the ground to intersect the flow of contaminated groundwater. Reactive material placed in the barrier removes the contaminants by one or more processes, including sorption, precipitation, oxidation, biodegradation, and encapsulation. In contrast with PRB walls, cutoff containment walls are low-permeability walls designed to isolate a contaminated area from the surrounding area. In addition to these remediation techniques, deep mixing can also be used for soil treatment by S/S. This includes the physical encapsulation and chemical fixation of contaminants in place through a range of processes, including sorption, precipitation, lattice incorporation, complexation, and encapsulation, as reported in Al-Tabbaa et al. (2012). A current growing trend is the use of shallow soil mixing techniques, such as ALLU mass stabilization (ALLU, 2010), for the S/S process.

Soil mix remediation is a cost-effective method with numerous technical alternatives and environmental advantages, including the applicability to sites of any size and to multiple contaminants. Water and soil contaminations consisting of heavy metals and/or organic contamination can be treated.

Combined with recent innovations in deep mixing equipment, this led in October 2008 to the start of the Soil Mix Remediation Technology (SmiRT) project (http://www-g.eng.cam.ac.uk/smirt). Within the framework of this project, a large-scale field trial was initiated on a contaminated site. Various deep mixing systems were used for this experimental campaign. The project studied the influence of several parameters, such as the type of binder as well as the installation variables, including speed of rotation, speed of penetration and withdrawal, and the number of mixing cycles. The setup of the field trials, the different deep mixing systems used for the remediation, and some test results are summarized by Al-Tabbaa et al. (2014), who also present some aspects of field observations, monitoring, in situ testing, coring, and laboratory testing on core samples.

Considering the industrial past of numerous countries throughout the world, soil mixing remediation technology certainly has a bright future.

11.4.7 Deep mixing for liquefaction mitigation

The deep mixing method can also be used to prevent soil liquefaction and post-liquefaction damage. Here, two case histories are presented to describe the growing use of the deep mixing technique.

The first case history, reported by Benhamou and Mathieu (2012), concerns the construction of two buildings on very soft alluvia in Martinique (France). These buildings are located in an area particularly exposed to seismic risks. For the construction of the two buildings, a new type of permanent foundation based on a Geomix caisson (as illustrated in Fig. 11.16) was chosen. The Geomix caissons are built to mitigate the risks of liquefaction damage. The arrangement (36×40 m) consists of a grid performed with the use of Geomix trenches. The Geomix technique is based on the hydrofraise technology combined with the CSM principle. Due to the strong inertia and the geometry of the caisson arrangement, the displacements of the Geomix panels are limited during earthquakes. Additional shear stress of the soil and horizontal forces from the structure are concentrated on Geomix bands, and liquefaction of the encased ground is avoided. This treatment also resists external post-liquefaction soil flow. Finally, the Geomix foundations reduce the settlements of the structure.

Another case history concerns the topic of liquefaction susceptibility restrained with the deep mixing method. Yamashita et al. (2013) discuss the measurements performed underneath a piled raft completed with grid-form deep cement mixing walls to reduce the risks of structural damage potentially caused by liquefaction. The structure is a 12-story office building.

Figure 11.16 Arrangement of the Geomix caissons made of CSM panels. *(Source: After Benhamou and Mathieu (2012), with courtesy of Soletanche Bachy).*

Figure 11.17 presents a schematic view of the building and foundation. Figure 11.18 illustrates the layout of piles and grid-form deep cement mixing walls.

The load distribution between the piles, the soil mix walls, and the surrounding soil was monitored for a period of 3 years. After the end of construction, settlements of 20 mm were recorded, as illustrated in Fig. 11.19. As shown in Fig. 11.20, 70% of the load was taken by the piles, 14% by the soil mix walls, and 15% by the soil. The measurements also show that the magnitude 9.0 Tohoku earthquake (March 11, 2011) had almost no effect on the settlements and on the load distribution.

The use of the deep mixing technique combined with typical foundation solutions is being increasingly used in seismic regions such as Japan. To determine the best-suited arrangement (between piles and soil mix elements), new methods of design are currently being developed, as explained in Matsui et al. (2013). The optimum arrangement is one with the lowest volume of treated soil that satisfies the safety limits as determined in the job specifications and standards.

Matsui et al. (2013) present the case of an hybrid application of soil–cement columns used in combination with soil mix walls to reinforce the

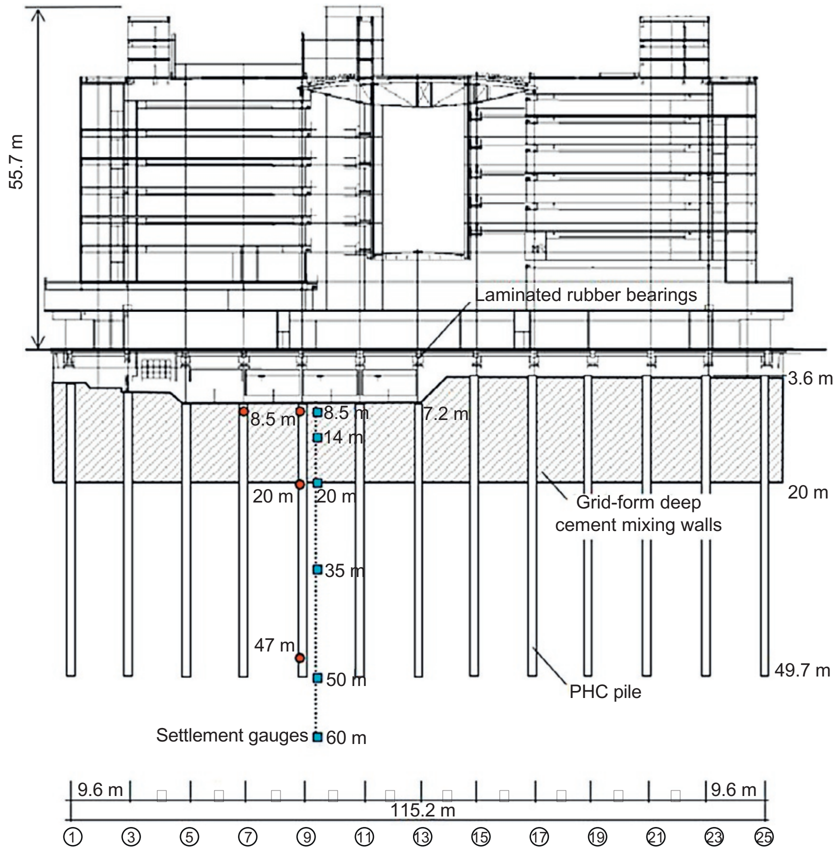


Figure 11.17 Schematic view of the building and foundation. *(Source: From Yamashita et al. (2013)).*

bearing capacity of the soil under an embankment. The basic concept of this method is to install soil mix walls into the ground directly under the slopes of the embankment in order to support the loads of the embankment and to mitigate the lateral movement of the ground. Soil–cement columns are placed both inside and outside the soil mix walls to restrict the vertical and horizontal deformations caused by the loads of the embankment. The authors propose a method to determine the optimum arrangement of the columns and the walls installed under the embankment.

11.5 CASE HISTORY OF HOPMARKT AALST (BELGIUM)

This section presents in detail a case history concerning the construction of a retaining wall in the Hopmarkt square in Aalst, Belgium.

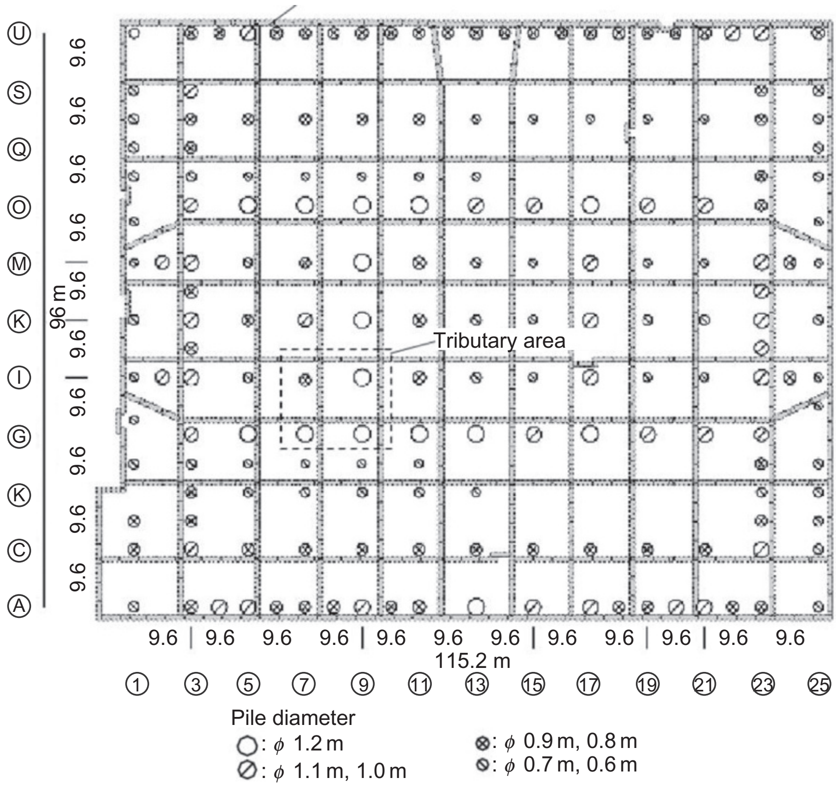


Figure 11.18 Layout of piles and grid-form deep cement mixing walls. *(Source: From Yamashita et al. (2013))*.

Within the framework of the Short Courses of the International Symposium on Ground Improvement held in Brussels in 2012, Eric Leemans from the firm Soetaert nv gave the details of the construction of a composite retaining wall in downtown Aalst. The excavation was dedicated to the construction of a three-story car park below ground level (12-m depth). Figure 11.21 shows the construction site. Dewatering of the area was not allowed because of settlement risks for the neighboring structures. The top soil layers presented a large amount of peat and soft loamy clay. Horizontal permeability inferior to 10^{-8} m/s was required in the project specifications, and the lateral displacement of the retaining walls was limited to 6 cm. For the design solution, a combination of techniques was envisaged with the realization of a composite retaining wall.

First, a CSM wall was constructed to a depth of 21 m into a clayey layer with low permeability. Then sheet piles were sunk into the fresh soil mix material to a depth of 15 m. Figure 11.22 illustrates the cross section of

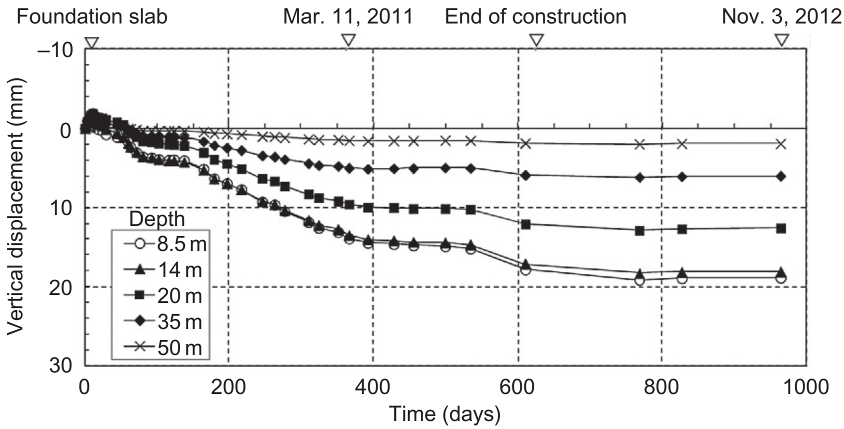


Figure 11.19 Measured vertical ground displacements below raft. *(Source: From Yamashita et al. (2013)).*

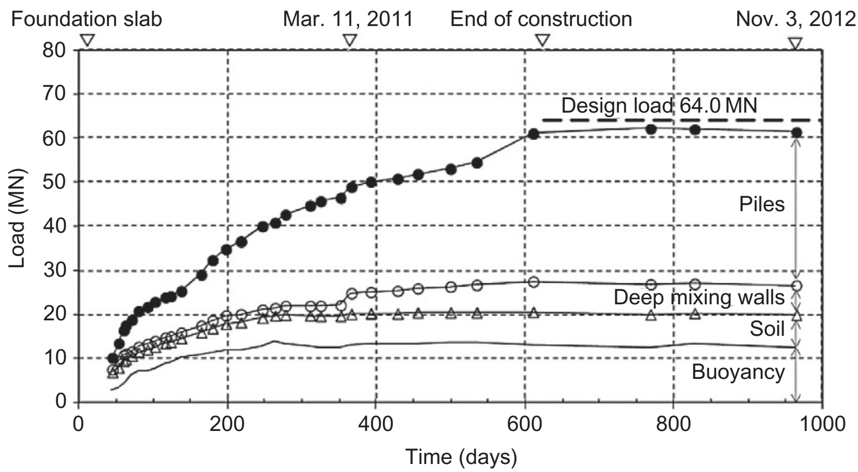


Figure 11.20 Time-dependent load sharing between raft and piles. *(Source: From Yamashita et al. (2013)).*

the CSM and sheet pile wall. Figure 11.23 shows the results of the cone penetration tests performed on the site. In this case, the CSM wall fulfilled a double mitigation function. The sheet pile wall could be installed without significant vibrations, avoiding the risk of damage to neighboring buildings. The CSM wall also had a temporary water retaining function. The dewatering of the building pit could therefore be carried out without significantly affecting the water level outside the building pit, which reduced the risk of

Figure 11.21 Excavation of the Hopmarkt square in Aalst (Belgium). *(Source: From Leemans (2012))*.

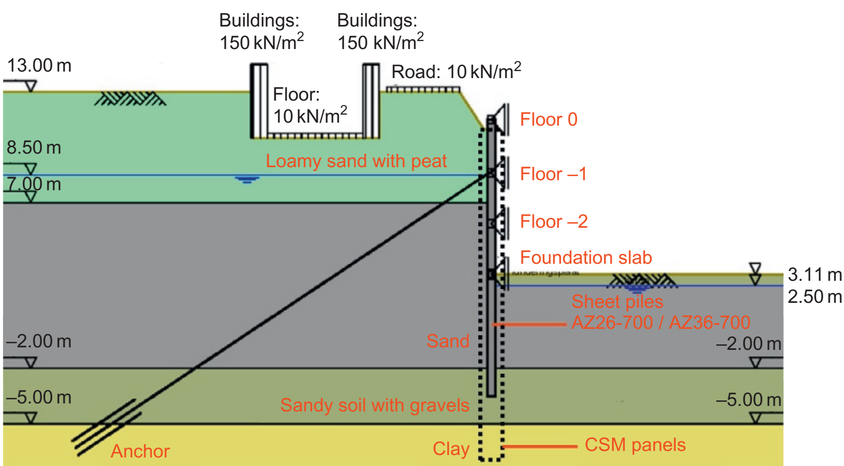


Figure 11.22 Cross section of the excavation. *(Source: After Leemans (2012))*.

settlement of the neighboring buildings. The sheet piles also have a double role. During and after construction, they provide stability to the excavation and they play the role of a permanent watertight barrier. Specific measures were therefore taken to ensure the waterproof qualities of the wall. The interlock of the double AZ sheet piles was welded before they were inserted

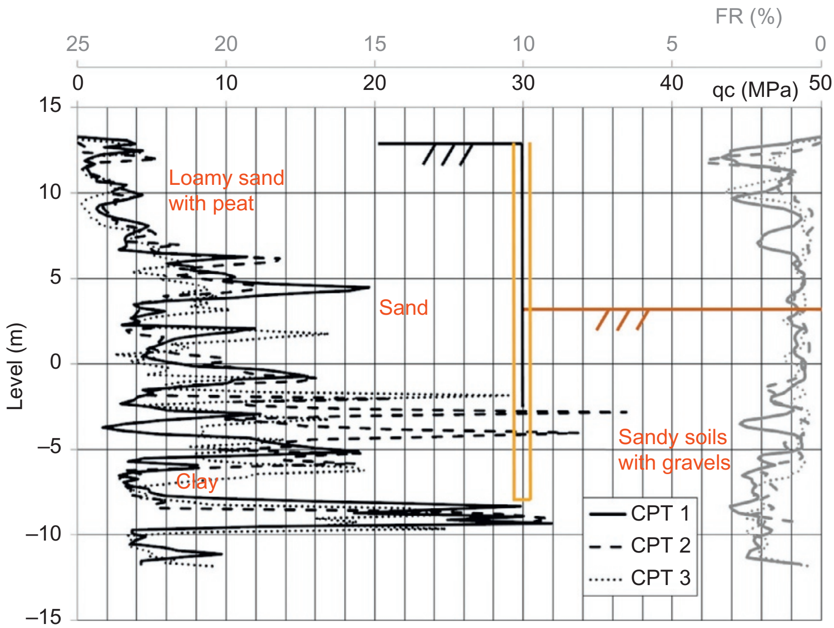


Figure 11.23 CPT results for the site of Hopmarkt Aalst (Belgium).

into the fresh soil mix material. In a similar manner, the anchorage lock and shoe were also welded before placing the sheet piles. The anchor lock was finally injected with expanding polyurethane foam. During excavation, the remaining interlocks between sheet piles were welded as well. Figure 11.24 illustrates the installation of the sheet piles into the fresh soil mix material, and Fig. 11.25 shows the progressive excavation and anchoring of the composite retaining wall.

The soil mix material of the CSM wall was investigated within the framework of the Belgian Building Research Institute (BBRI) Soil Mix Project (2009–2013). Extra CSM panels were executed on the same site with similar execution parameters and slurry properties. After a few days of hardening, these CSM panels were excavated and transported to the laboratory facilities of the BBRI. As described in Table 11.6, the soil mix material was investigated using typical tests performed on core samples and also large-scale tests conducted on large soil mix elements. The first extra CSM panel was cored and cut to obtain core samples and large soil mix blocks in order to perform large-scale UCS tests, such as described in Vervoort et al. (2012). The large-scale UCS tests were conducted to investigate the scale effect and the influence of the unmixed soft soil inclusions included in

Figure 11.24 Installation of the sheet piles into the fresh soil mix material. *(Source: After Leemans (2012)).*

Figure 11.25 Progressive excavation and anchoring of the composite retaining wall. *(Source: After Leemans (2012)).*

the soil mix matrix. The other two extra panels were used for the realization of four large-scale bending tests on half CSM panels. The procedure and the results of these tests were published in Denies et al. (2014, 2015a). These bending tests were performed within the framework of a large experimental

Table 11.6 Mechanical characterization of the soil mix material executed in Aalst (BBRI Soil Mix Project, 2009–2013)

Tests on core samples performed in the laboratory facilities of the BBRI	
UCS according to EN 12390-3 (2009)	7.31 MPa (average value of 31 tests performed on core samples with diameter and height of 105 mm)
Modulus of elasticity, E,[a] according to NBN B15-203 (1990)	8.40 GPa (average value of 4 tests performed on core samples with a diameter of 105 mm and a height of 210 mm)
Tensile splitting strength according to EN 12390-6 (2010)	1.31 MPa (average value of 7 tests performed on core samples with diameter and height of 105 mm)
Volume percentage of unmixed soft soil inclusions into the soil mix material, according to the test procedure of Denies et al. (2012c)	2.6% (obtained on 25 core samples)
Porosity according to NBN B 15-215 (1989)	47.2% (obtained on 4 core samples)
Coefficient of permeability according to DIN 18130-1 (1998)	$<8 \times 10^{-11}$ m/s (obtained on 4 core samples)
Results of two large-scale UCS tests performed on large soil mix samples at KU Leuven	
UCS	5.2 and 4.1 MPa (respectively obtained on rectangular blocks with dimensions $54 \times 50 \times 119$ cm and $54 \times 79 \times 119$ cm)
E_{tg} (tangent)[b]	6.0 and 6.0 GPa
E_{sec} (secant)[b]	6.7 and 6.8 GPa

[a] E is determined in a tangent way varying the applied load between 10% and 30% of the estimated UCS. The deformations of the sample are measured along three axes using DEMEC mechanical strain gages.
[b] Measurement performed with four linear vertical displacement transducer (LVDT) devices with measurement base of approximately one-fourth of the height of the block, installed around the center of each vertical side. The tangent modulus corresponds to the local slope of the stress–strain curve at 50% of the peak strength. The secant modulus is the slope of a straight line joining the origin with the point on the curve at 50% of the peak strength.

campaign of 17 large-scale bending tests conducted to assess the real contribution of the soil mix material to the bending resistance of the soil mix wall.

11.6 CONCLUSION

This chapter introduced the reader to the different construction principles and available equipment for the performance of the deep mixing method.

The chapter also discussed the applications of this technique. Used for ground improvement for more than 50 years, the deep mixing method is being increasingly applied as alternative to traditional foundation and excavation systems or for environmental purposes.

The chapter illustrated the huge field of applications of the method (as reported in Table 11.5). Today, when designers are searching for the best solution to an engineering issue, the deep mixing method is increasingly being considered in the design process. Nevertheless, it is necessary to analyze the problem considering the applicability of the method, the possible uses of the deep mixing equipment, and the produced soil mix material. Figure 11.26 presents these first considerations for determining if the deep mixing method may be an alternative for a particular construction project.

For temporary constructions, the mechanical characteristics of the soil mix material are generally well mastered. The strength and stiffness of the material can be assessed, as well as its adherence with steel. Its permeability can also be determined in the laboratory or with the use of in situ permeability tests. Nevertheless, the durability of the soil mix material with a permanent function remains a controversial topic. As previously mentioned, design criteria of permanent soil mix elements may be based on the execution monitoring (of the mixing energy, depth, etc.) and on performance tests including UCS, freeze–thaw and wet–dry durability, leachability

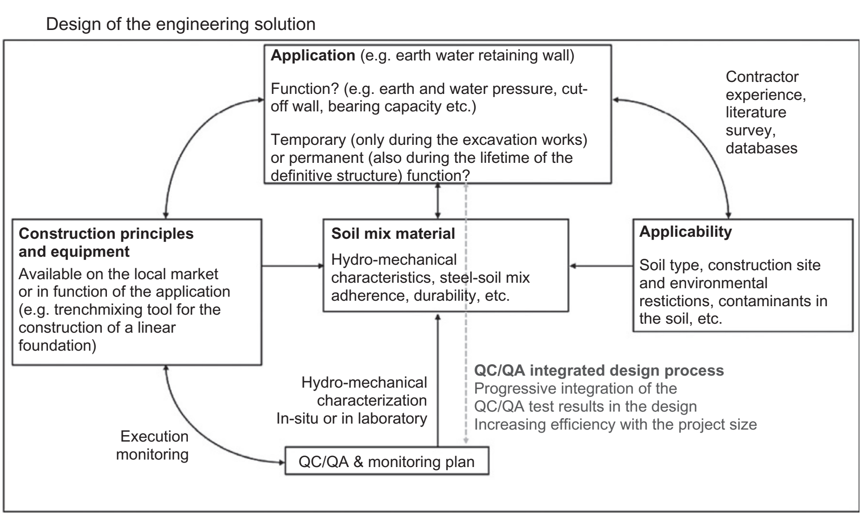


Figure 11.26 First considerations of design for a deep mixing project.

(in particular cases), porosity, and permeability (if required) tests. However, the situation is more complex when contaminants are present in the ground.

Quality control (including execution monitoring) was not highlighted in this chapter. Nevertheless, it remains an essential stage of the construction process. The reader can refer to the following references to obtain information relative to this subject: Maswoswe (2001), EuroSoilStab (2002), Porbaha (2002), Larsson (2005), EN 14679 (2005), Terashi and Kitazume (2011), Denies et al. (2012c), Leoni and Bertero (2012), Filz et al. (2012), FHWA (2013), and Geotech Tools (Iowa State University, 2010–2014).

Deep mixing technology is characterized by continuous innovation with regard to equipment. Considerable experience has been acquired by deep mixing contractors and design engineers, the result of which is the publication of several standards and codes. The European Standard EN 14679 (2005), for example, was elaborated under the umbrella of CEN TC 288 "Execution of Special Geotechnical Works." Nevertheless, although progress has been made in standardization, in practice it seems that there remains a need to develop guidelines for pragmatic aspects, especially regarding quality assurance/quality control (QA/QC) procedures and design. Moreover, the design process of some particular soil mix structures, such as retaining walls, remains vague in most countries. Flexible QA programs that comply with the variable character of the soil mix material should be elaborated in parallel with specific design requirements adapted to the function of the soil mix elements. The publication of the design manual of the FHWA (2013), which concentrates not only on the execution of the method but also on the design aspects of deep mixing applied for embankment and foundation support, is in agreement with that philosophy. For earth–water retaining walls and cutoff walls, new design rules will soon be published jointly by BBRI and SBRCURnet.

In this handbook, the design approach and the QC/QA activities are directly related to the field of application of soil mix walls, to the project restrictions, and to the category of the structure (according to the principles of Eurocode 7—EN 1997-1, 2004). In the future, such guidelines should be developed for each type of application of the deep mixing method.

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