General Report
SESSION 4 – SOIL MIXING 2 – DEEP MIXING

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ABSTRACT

The present General Report highlights the significant contributions of the papers of Session 4 of the IS-GI Brussels 2012 dedicated to Deep Mixing. As not all papers are reviewed in detail, references are given in order to provide a balanced overview of the entire Technical Session.
This General Report discusses the latest developments and current researches in the deep soil mix (DSM) technique. Different ***execution processes*** *are summarized or classified and their mechanisms are outlined. The* ***DSM material*** *is discussed in detail and various* ***applications*** *of the process are illustrated with the help of case histories. Indeed, during several decades, the DSM technique has been used for ground improvement (GI) applications, but in recent years, DSM was also dedicated to various structural and environmental functions: earth/water retaining structures, foundations, soil reinforcement, land levees and slope stabilization, in situ remediation and barriers against liquefaction. In the present report, the temporary and permanent characters of the DSM structures are also mentioned with regard to the durability aspects of the soil mix material. Current* **Quality Assurance/Quality Control activities** *for DSM projects are highlighted.* ***Design*** *of in-situ soil mixing in geotechnical practice is reappraised considering the nature of the DSM material. Many references on the topics discussed are also given in the report.*

1. INTRODUCTION

The DSM process was introduced in the 70's in Japan and in the Scandinavian countries. Since several decennia, DSM has been known as a Ground Improvement (GI) technique, as reported in Porbaha et al. (1998 and 2000). Porbaha has notably proposed a terminology for the DSM technology, as presented in Table 1. According to the classification of GI methods adopted by the ISSMGE TC 211 Ground Improvement, formerly TC 17, DSM can be classified as ground improvement with grouting type admixtures, as illustrated in Table 2 (Chu et al. 2009). A lot of reviews describing various Deep Mixing Methods (DMM) are available in Terashi (2003), Topolnicki (2004), Larsson (2005), Essler and Kitazume (2008) and Arulrajah et al. (2009). In parallel, the results of national and European research programs have been published in multiple interesting reports (such as Eurosoilstab, 2002), while also the European standard for the execution of deep mixing "Execution of special geotechnical works – Deep Mixing" (EN 14679) was published in 2005. Most of these research projects focused on the global stabilization of soft cohesive soils such as peat, clay, gyttja and silt.

Table 1: Terminology of the deep mixing family, after Porbaha (1998)

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

Table 2: Classification of GI methods adopted by TC211, formerly TC 17 (after Chu et al., 2009)

D. Ground improvement with grouting type admixtures	D1. Particulate grouting	Grout granular soil or cavities or fissures in soil or rock by injecting cement or other particulate grouts to either increase the strength or reduce the permeability of soil or ground.
	D2. Chemical grouting	Solutions of two or more chemicals react in soil pores to form a gel or a solid precipitate to either increase the strength or reduce the permeability of soil or ground.
	D3. Mixing methods (including premixing or deep mixing)	**Treat the weak soil by mixing it with cement, lime, or other binders in-situ using a mixing machine or before placement.**
	D4. Jet grouting	High speed jets at depth erode the soil and inject grout to form columns or panels.
	D5. Compaction grouting	Very stiff, mortar-like grout is injected into discrete soil zones and remains in a homogeneous mass so as to densify loose soil or lift settled ground.
	D6. Compensation grouting	Medium to high viscosity particulate suspension is injected into the ground between a subsurface excavation and a structure in order to negate or reduce settlement of the structure due to ongoing excavation.

2. CONSTRUCTION PRINCIPLES AND EQUIPMENT

In the DSM process, the ground is in situ mechanically (and possibly hydraulically or pneumatically) mixed while a binder, based on cement or lime, is injected with the help of a specially made machine. DMM can be classified according to its execution process. Two types of installation methods are generally considered with regard to 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 with the soil. Depending on the type of soil and binder, a mortar-like mixture is created which hardens during the hydration process (Essler and Kitazume, 2008). In the dry soil mixing process, the binder is directly mixed with the soil. The binding agents directly react with the prevailing soil and the contained water and form a soil mortar. In the present proceedings, Quasthoff (2012) provides a State of the Art in dry soil mixing and reviews its construction principles, its equipment and its field of applications.
Depending on the applications, different improvement patterns can be designed with the wet and dry mixing methods with the help of soil-cement columns, rectangular soil mix panels, continuous barriers or global mass stabilization. In the present symposium, different types of DSM systems are presented, as reported hereunder.

2.1. Soil-cement column systems

2.1.1. CVR C-mix® system

The CVR C-mix® is performed with an adapted bored pile rig and a specific designed shaft and mixing tool. This tool rotates around a vertical axis at about 100 rpm and cuts the soil mechanically. Simultaneously, the water/binder mixture (w/b weight ratio between 0.6 and 0.8), is injected at low pressure (< 5 bar). The injected quantity of binder amounts mostly to 350 and 450 kg binder/m³, depending on the soil conditions and specifications. The binder partly (between 0% and 30%) returns to the surface, as 'spoil return'. The resulting DSM elements are cylindrical columns with diameter corresponding to the mixing tool diameter, varying between 0.43 and 1.03 m. As a wide range of tools has seen the light of day in the field of DSM technology, recent developments have mainly taken place in the optimization of tools for mass production in particular with the design and construction of triple (or more) auger systems. In this way, a CVR Twinmix® and a CVR Triple C-MIX® have been designed to increase the production rate. Figure 1 illustrates the CVR C-mix® machine and its Triple version.

2.1.2. SMET Tubular Soil Mix (TSM®) system

As represented in Fig. 2, the TSM® technique uses a mechanical and a hydraulic way of mixing. Apart from the rotating (around the vertical axis) mixing tool, the soil is cut by the high pressure injection (till 500 bars) of the water/binder mixture. The resulting DSM elements are cylindrical columns with a diameter between 0.38 and 0.73 m. Again, a twin and a triple version exist (Denies et al., 2012a).

a) b)

Figure 1: a) The CVR C-mix® machine (single auger system) and b) its Triple version, after Denies et al. (2012a)

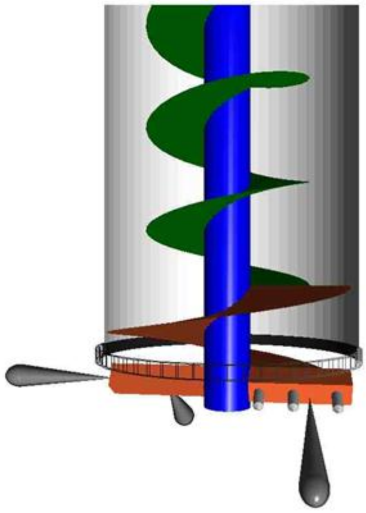

Figure 2: Scheme of the TSM® system (Smet-F&C), after Denies et al. (2012a)

2.1.3. Keller Foundations FLAPWINGS® system

Within the framework of the European Research project INNOTRACK which is presented in paragraph 4.2, SNCF, Keller Foundations and IFSTTAR tested the feasibility of an alternative soil reinforcement technique the FLAPWINGS, based on vertical soil-cement mixed columns with variable diameter (Lambert et al., 2012). Keller Foundations has designed the FLAPWINGS soil mix tool with the purpose of executing soil-cement columns in a railway environment. This is a wet soil mixing system. As illustrated in Fig. 3, it consists of a 150 mm core retractable tool able to open up in order to perform the soil mixing phase on a 600 mm diameter column. The opening and closing of the retrieval blades are ensured with the help of a two way hydraulic jack located in the mixing tool.

2.1.4. Soletanche Bachy SPRINGSOL® system

Within the framework of the Rufex project (reinforcement and re-use of railway tracks and existing foundations, see paragraph 4.2 for a presentation of the project), soil-cement columns were installed with the help of the Soletanche Bachy 'Springsol' wet soil mixing tool (Guimond-Barrett et al, 2012a). As illustrated in Fig. 4, 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 insertion into a temporary casing. By increasing the length of the mixing blades, the column diameter can be adapted (e.g. 400 and 600 mm as illustrated in Fig. 4). The binder is delivered through outlet holes in the drag bit located at the bottom end of the tool. The main interest of the Springsol tool is the possibility to reinforce the ground under an existing railway track.

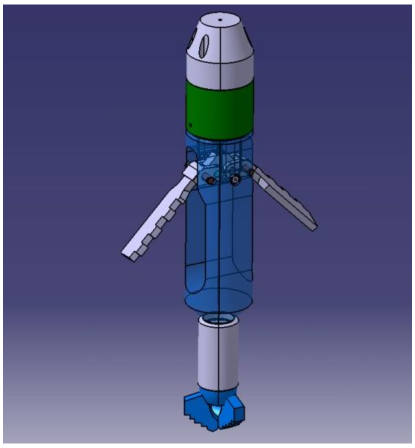

Figure 3: FLAPWINGS® system (Keller Foundations), after Lambert et al. (2012)

Figure 4: Soletanche Bachy Springsol® systems with 400 mm (left) and 600 mm (right) diameters, after Guimond-Barrett et al. (2012a)

2.1.5. *Other developments*

Figure 5 illustrates the two single auger systems used in the framework of the SMiRT research project (Al-Tabbaa et al., 2012). The first one consists of standard single auger which can be directly mounted on the end of a continuous flight auger (CFA) pile shaft (see Fig. 5a). The second one is the double rotary head auger system developed by Eco Foundations (see Fig. 5b).

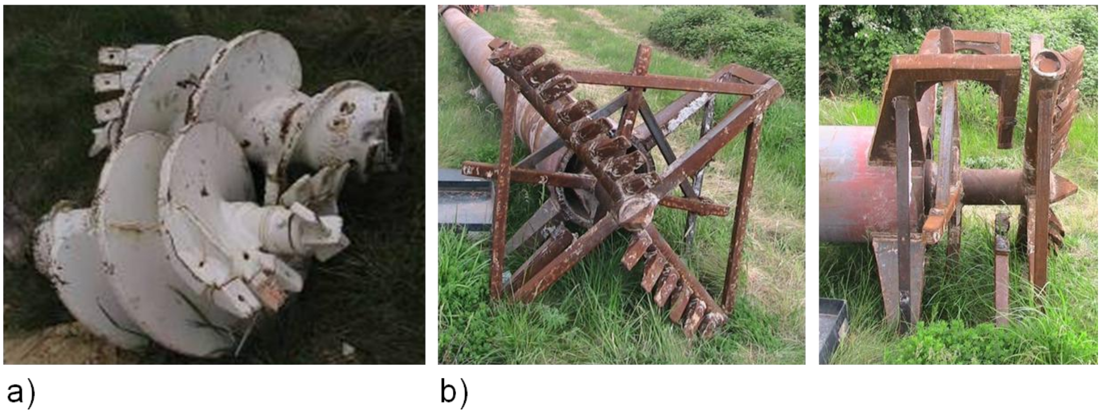

Figure 5: Single auger systems: (a) standard single auger system (b) double rotary head auger, after Al-Tabbaa et al. (2012)

Within the framework of a land levee project in New Orleans (the LPV111 project), two different technologies were applied to treat over 1.3 million cubic meters of foundation soil: the Trevi Turbo Mix (TTM), in single and double versions, and the Contrivance Innovation Cement Mixing Columns (CI-CMC), as reported in Leoni and Bertero (2012). These innovative and distinct wet soil mix systems are able to produce large (1.6 m diameter), uniform, and continuous improved columns.

2.2. CSM panels

The execution of soil mix rectangular panels can easily be performed with the help of the Cutter Soil Mixing (CSM) system, recently 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 mainly used for the construction of cut-off 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 (w/b) mixture is being introduced, soil formations are easily penetrated, broken down, and mixed with the w/b mixture, using the cutter wheels as cutting and mixing tool. As illustrated in Fig. 6, the two cutting wheels rotate independently about a horizontal axis and cut the soil. At the same time, the water/binder mixture is injected at low pressure (commonly < 5 bar) with w/b ratio chosen in function of the design strength and permeability. The injected quantity of binder amounts mostly to 200 and 400 kg binder/m³. Again, spoil return usually ranges between 0% and 30%. The CSM system is in operation since 2003 and it is commercially available.

Figure 6: The cutting wheels of the CSM machine

2.3. Trenchmix method

The Trenchmix method produces a soil mix barrier, up to a depth of 10 m, in a single continuous pass which is an advantage particularly in case of water retaining function (no joints). The Trenchmix uses cutting tools as shown in Fig. 7 to mix trenches. It has a dry and a wet method. Figure 7 shows the dry method.

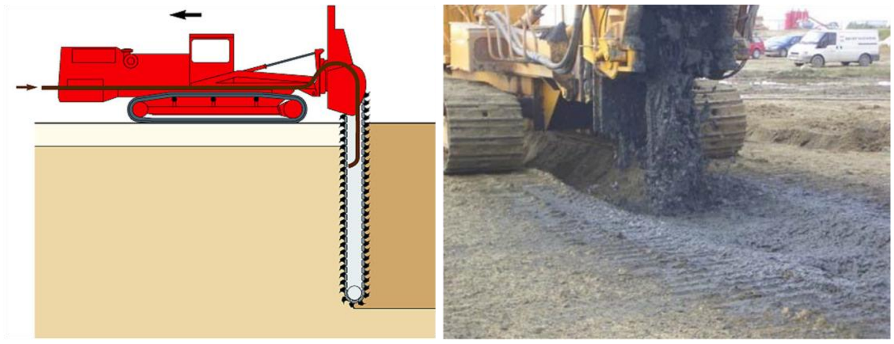

Figure 7: Trenchmix method (after Borel, 2007)

2.4. ALLU® mass stabilization

The ALLU® mass stabilization system is developed for mass stabilization of soil. It has a dry and a wet method. It was in particular used within the framework of the SMiRT project for land remediation (Al-Tabbaa et al., 2012). Figure 8 illustrates this system, which consists of a power mix mounted on the dipper arm of an excavator with a pair of mixing drums at the end and a pressure feeder mounted on a powered crawler chassis which delivers dry binder into the ground with the aid of compressed air (ALLU, 2010).

Figure 8: The ALLU® system used in the ground improvement treatment sections (Al-Tabbaa, 2012)

In general, the various DSM equipments presented in this paragraph allow the execution in a large range of soils with the following advantages:

- the use of the existing soil as a construction material,
- the independence with regard to the supply of fresh concrete (delay due to traffic jams),
- the limited spoil return (in comparison with jet grouting),
- a control of the geometry of the DSM element with depth,
- and the absence of important vibrations during the execution process.

3. DEEP SOIL MIX MATERIAL

3.1. Governing parameters

Several parameters have an influence on the produced DSM material. Terashi (1997) highlights the factors affecting the strength of the DSM material, as illustrated in Table 3. The DSM material quality depends on the cement type and content, on the in situ soil and on the execution process. The hardening agent is usually a mixture of cement and/or lime, water (for wet mixing), and in several cases bentonite. Sometimes ashes and gypsum are used as additive.

Table 3: Factors affecting the strength of the DSM material, after Terashi (1997)

I. Characteristics of hardening agent	1. Type of hardening agent 2. Quality 3. Mixing water and additives
II. Characteristics and conditions of soil	1. Physical chemical and mineralogical properties of soil 2. Organic content 3. pH of pore water 4. Water content
III. Mixing conditions	1. Degree of mixing (Mixing energy) 2. Timing of mixing/re–mixing 3. Quantity of hardening agent
IV. Curing conditions	1. Temperature 2. Curing time 3. Humidity 4. Wetting and drying/freezing and thawing, etc.

The water/binder weight ratio also plays a major role in the mechanical/durability characteristics of the material. Moreover, the nature of the ground has a huge impact on the strength and uniformity of the material. For example, stiff cohesive soils do not allow an effective mix of the components, which can lead to the presence of unmixed material in the DSM element. Finally, the final product will be the result of a given DSM system available on the local market. There are a lot of differences between the various systems – especially with regard to the drilling/mixing tools – and the execution process influences the quality of the DSM material in terms of strength, uniformity and continuity.

3.2. Hydro-mechanical characterization of DSM material

In the context of the European standardization and for the purpose of investigating these questions, in 2009, the Belgian Building Research Institute (BBRI) initiated the "Soil Mix" project in collaboration with KU Leuven and the Belgian Association of Foundation Contractors (ABEF). In the framework of this research, numerous tests on in situ DSM material have been performed. A good insight has been acquired with regard to strength and stiffness characteristics that can be obtained with the C-mix®, the TSM® and the CSM systems in several Belgian soils. All the results and the developments related to the BBRI "Soil Mix" project are detailed in four papers of the present symposium:

- Denies et al. 2012a. *SOIL MIX WALLS as retaining structures – Belgian practice,*
- Denies et al. 2012b. *SOIL MIX WALLS as retaining structures – Mechanical characterization,*
- Denies et al. 2012c. *Mechanical characterization of DEEP SOIL MIX material – procedure description,*
- Vervoort et al. 2012. *Mechanical characterization of large scale soil mix samples and the analysis of the influence of soil inclusions.*

Main results of the BBRI "Soil Mix" project are presented in the present paragraph.

Bellato et al. (2012) present the results of a laboratory study carried out on DSM samples from more than 50000 m^2 CSM panels performed for the construction of the new railway station in Bologna (Italy). The subsoil is constituted mostly by overconsolidated clays. Hydraulic and mechanical laboratory tests were conducted at different curing time, from 14 days to more than 2 years, to study the influence of curing time on the properties of the mixture.

In a first step, the BBRI "Soil Mix" project focused on the mechanical characterization of the DSM material with regard to the sampling of cores from soil mix walls (SMW), its unconfined compressive strength UCS (1073 tests, up to now), its modulus of elasticity E (152 tests) and its tensile splitting strength (95 tests). Moreover, the influence of unmixed soft soil inclusions in the soil mix on the material characteristics was also analyzed. In parallel, numerous tests dealing with ultrasonic pulse velocity, porosity, permeability and adherence with steel reinforcement have been launched (Denies et al., 2012b).
In the framework of the research program, long term behavior is currently investigated with the help of creep tests and considering the effect of time on the UCS. Indeed, while SMW were previously used only for temporary excavation support, permanent retaining and foundation applications with soil mix are increasingly applied. Hence, durability aspects of DSM material have to be considered not only with regard to its mechanical properties but also from a chemical point of view.
In the second period of the research program, the DSM material shall be investigated in terms of its alkalinity properties, with the help of pH long term measurements, in order to evaluate its level of corrosion protection. The viability of the process in presence of polluted soils shall also be considered.

Finally, a design method for the soil mix structures, accounting for the presence of heterogeneities and soil inclusions, the scale effects and the time effects shall be developed.

During the first part of the experimental campaign, cores of DSM material have been drilled at 38 Belgian construction sites, with different soil conditions and for various DSM systems. Details of the tests are given in Denies et al. (2012b). Figure 9 illustrates the correlation between the modulus of elasticity and the UCS of the tested DSM material, without distinction of the soil type.

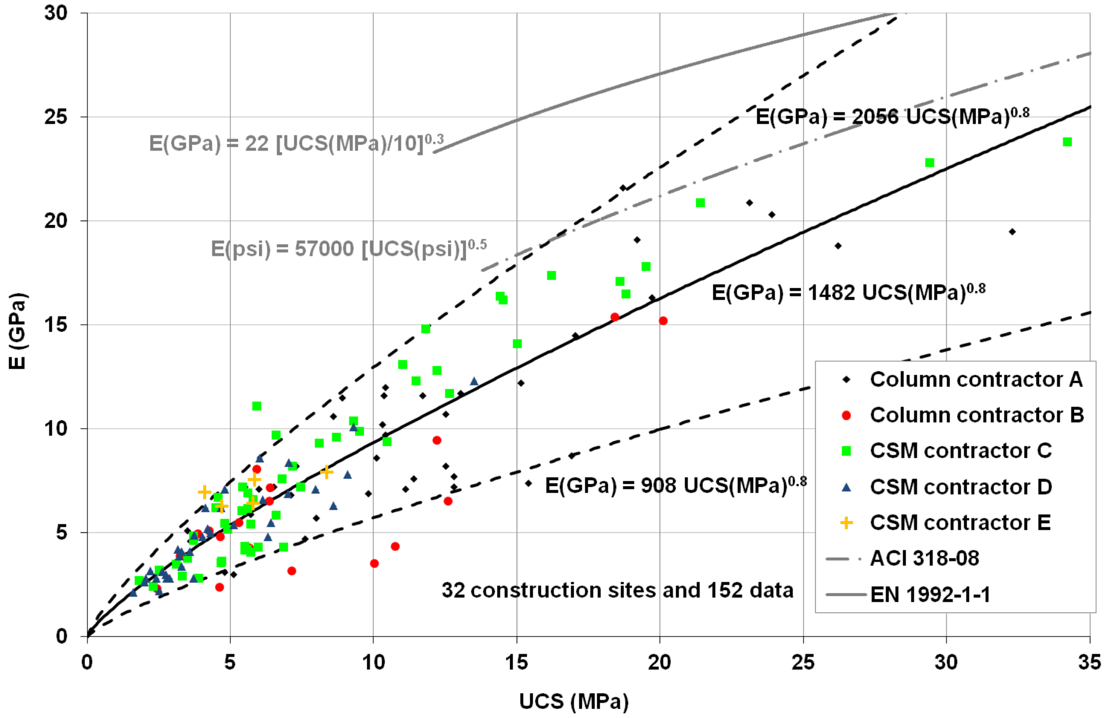

Figure 9: Relationship between the modulus of elasticity and the UCS of DSM material, after Denies et al. (2012b)

The samples were tested after a period ranging between 30 and 200 days. Since the aim is to determine the correlation between the modulus of elasticity and the UCS, the test results are not corrected for the age of the samples.
The best fit corresponds to:

$$E = 1482\, UCS^{0.8} \tag{1}$$

with a coefficient of determination close to 0.80 (-). Lower and higher 5% quantile estimations of E respectively correspond with:

$$E = 908\, UCS^{0.8} \tag{2}$$

and

$$E = 2056\, UCS^{0.8} \tag{3}$$

These estimations are valid for the range 1.5 MPa < UCS < 35 MPa.
In Fig. 9, relationships for normal concrete, from ACI 318-08 and EN 1992-1-1, are given for comparison. According to ACI 318-08**,** the modulus of elasticity for normalweight concrete can be defined with regard to the UCS with the help of the following equation:

$$E\,(psi) = 57000\sqrt{UCS\,(psi)} \tag{4}$$

where E is defined as the secant modulus of elasticity between 0 and 45% ($\sigma_{40\%UCS}$) of the UCS. Based on previous research of Pauw (1960), equation (4) is valid for UCS values larger than 2000 psi (or 13.8MPa).
Eurocode 2 (EN 1992-1-1) provides the following relationship for concrete:

$$E(GPa) = 22[UCS(MPa)/10]^{0.3} \quad (5)$$

where E is the secant modulus of elasticity between 0 and 40% ($\sigma_{40\%UCS}$) of the UCS. Equation (5) is only valid for concrete samples containing quartzite aggregates and for a range of UCS varying between 12 and 90 MPa.

Figure 10 gives the relationship between the tensile splitting strength (T) and the UCS, without distinction of the soil type. The samples were tested after a period varying between 32 and 200 days. Test results are not corrected for the age of the sample. In Fig. 10, experimental results for DSM cores are compared with well-established empirical relationships for concrete.

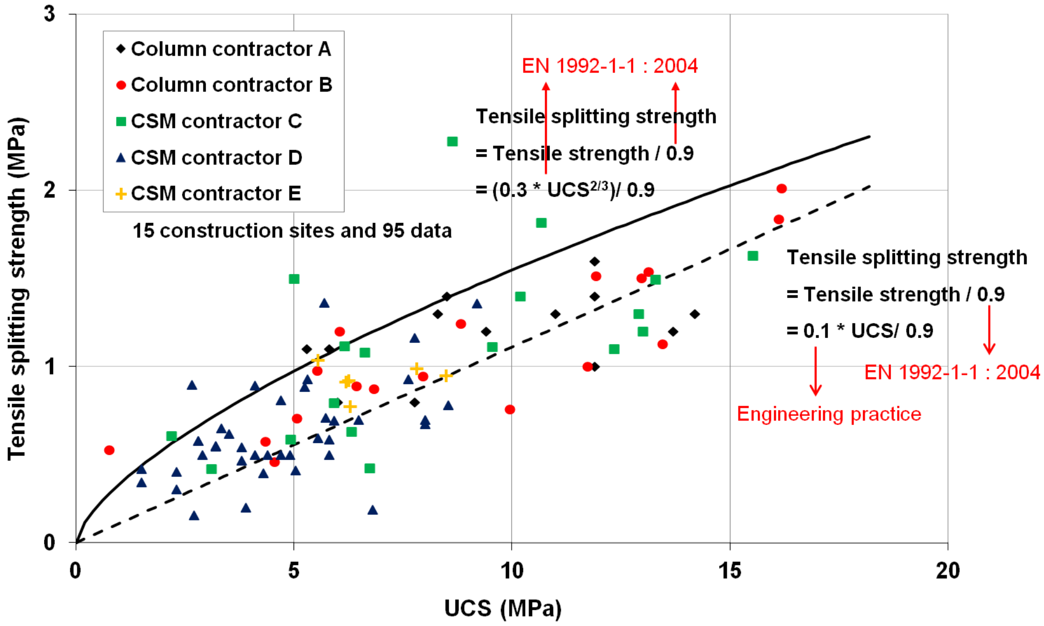

Figure 10: Relationship between the tensile splitting strength and the UCS of DSM material, after Denies et al. (2012b)

According to Eurocode 2 (EN 1992-1-1), when the tensile strength is determined as the splitting tensile strength, an approximate value of the axial tensile strength, T_a, may be determined as:

$$T_a = 0.9T \quad (6)$$

Eurocode 2 also provides a correlation with the UCS:

$$T_a = 0.30\ UCS^{2/3} \quad (7)$$

which is only valid for concrete with UCS values less than the UCS of the C50/60 concrete type.
In the engineering practice, the axial tensile strength of concrete is often related to the UCS by the following relationship:

$$T_a = 0.1UCS \quad (8)$$

It is interesting to note that Bellato et al. (2012) obtained a similar range of values for the modulus of elasticity and the tensile splitting strength of DSM material performed with CSM technology applied in overconsolidated clays.

In Denies et al. (2012b), the coefficient of hydraulic conductivity varies between 10^{-8} and 10^{-12} m/s, regardless of the soil conditions. In overconsolidated clays, Bellato et al. (2012) measured coefficients of permeability around 10^{-11} m/s.

In both studies, results of petrographic analysis are also presented in order to obtain a microscopic view of the DSM material.

In Denies et al. (2012b), porosity values were measured and vary between 25 and 65% for all soil types.

Due to the specific DSM procedure, unmixed soil inclusions are inevitable. Within the framework of the BBRI 'Soil Mix' research, all inclusions in DSM material are considered as unmixed soft soil inclusions. A methodology taking into account these inclusions was developed and illustrated with case studies of DSM material executed in several Belgian soils. This methodology is summarized in Denies et al. (2012c) and detailed in Ganne et al. (2011 and 2012). Figure 11 gives an overview of the results for 27 Belgian construction sites.

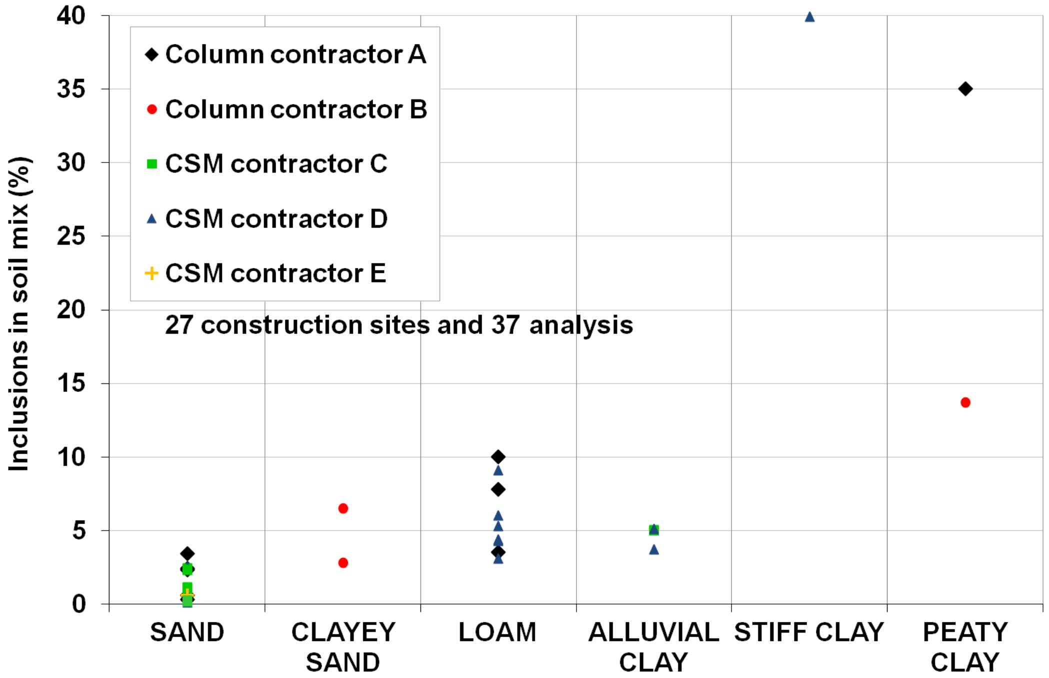

Figure 11: Percentage of soil inclusions in DSM material, after Denies et al. (2012b)

The amount of soil inclusions in DSM material mainly depends on the nature of the soil:

- in quaternary or tertiary sands, it is less than 3.5%,
- in silty (or loamy) soils and alluvial clays, it ranges between 3 and 10%,
- in clayey soils with high organic content (such as peat) or in tertiary (overconsolidated) stiff clays, it can amount up to 35% and higher.

One major issue concerns the representativeness of the core samples with regard to the in situ executed DSM material. On the one hand, there is the question of the scale effect and on the other hand, the question of the influence of soil inclusions. Both have an influence on the UCS test results. To investigate these topics, an experimental, as well as a numerical simulation research program has been initiated at KU Leuven (Vervoort et al., 2012).

As the design and the Quality Control (QC) of the execution process are generally based on laboratory tests performed on cored material, each sample is characterized by its own history influencing the test results and its interpretation. Beyond the question of the representativeness of the core samples with regard to the in situ executed material, Denies et al. (2012c) concentrate on the sampling, the transport, the storage, the handling and the preparation of the DSM test specimens and propose test procedures in the continuity of the content of the European standard EN 14679 (2005) for deep mixing.

Due to the DSM procedure, it is partly to be expected that the mixed material is not perfectly homogeneous. In other words, inclusions of poorly mixed or even unmixed (i.e. soil) material are present. The amount of such inclusions can be less than 1% of the total volume at some sites, but 10% or more is also observed (as illustrated in Fig. 11). Some of these inclusions are very small, while in other cases they can have dimensions of several centimeters. It is generally assumed that below a certain volume percentage and/or for small dimensions of the individual inclusions, these inclusions have no negative impact on the behavior and on the strength of the SMW. To quantify the maximum acceptable limits of volume percentages, an experimental as well as a numerical simulation research program has been initiated (Vervoort et al., 2012). This research aims also to better understand the behavior of this material and the failure of it.

The experimental part of the research focuses on laboratory experiments. The behavior in laboratory is certainly affected by the scale and the dimensions of the test samples. Apart from traditional cores (e.g. with a diameter of about 10 cm), large scale tests are being conducted on rectangular blocks with approximately a square section, with a width corresponding to the width of the in situ wall (about half a meter) and with a height approximately two times the width (see Fig. 12.a). The influence of the scale effect was found to be limited for the Young's modulus. The UCS values of the large samples show a reduction of 30 to 50% in comparison to these of the 10 cm diameter cores.

By conducting numerical simulations (2D), one tries to better understand the effect of unmixed soft soil inclusions, i.e. the effect of their size, total surface percentage, the number of inclusions, the relative position, etc. Three approaches with increasing complexity are conducted:

- elastic models, whereby the focus is on the material stiffness,
- elasto-plastic models, whereby apart from the stiffness, the strength is analyzed,
- and a discontinuous approach, whereby individual fracture initiation and growth can be modeled, apart from the stiffness and strength (see Fig. 12 b and c).

The most prominent conclusion is that even a small percentage of inclusions has a significant effect on the DSM strength. For a mere 1% of unmixed material, the strength is reduced by 20%, while for 10% of unmixed material about half of the strength disappears. The effect on the stiffness is more limited. Another consistent result is that other characteristics than the total surface percentage of unmixed material can have a significant effect, e.g. large sharp-ended individual inclusions have a negative effect on the strength and stiffness.

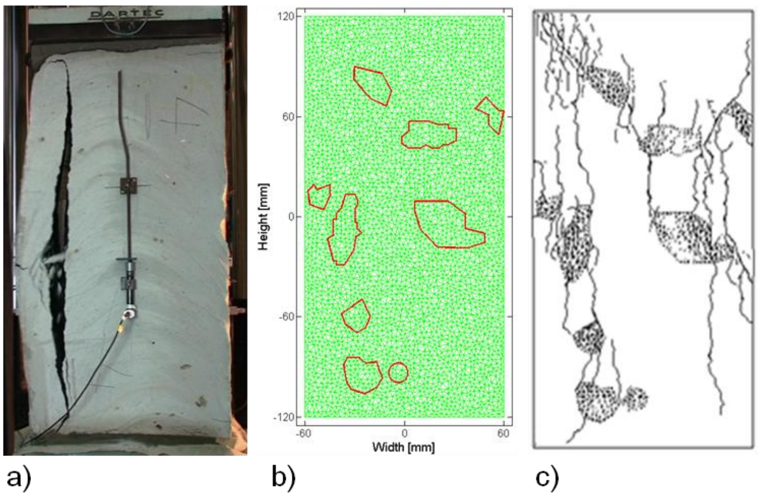

Figure 12: a) Large scale test on DSM material (block of dimensions 61 × 53 × 124 cm), b) Mesh generated for the discontinuous simulations of a sample with dimensions 120×240 mm (red lines indicate the soil inclusions) and c) Simulated fracture pattern of the model, after Vervoort et al. (2012)

3.3. Mixing and curing conditions

3.3.1. Mixing degree and homogeneity of the DSM material

At the present time, a wide variety of different machines and tools are available on the market for in situ deep mixing. As reported in Topolnicki and Pandrea (2012), the mixing technology has to ensure that the soil is mixed sufficiently with the binder to achieve a homogeneous product with a low coefficient of variation for its strength. The quality control of mixing can be performed with regard to the "*Blade rotation number*", as introduced in the CDIT (2002):

$$\mathrm{BRN} = \sum \mathrm{M} \, \mathrm{x} \left(\frac{\mathrm{N_d}}{\mathrm{V_d}} + \frac{\mathrm{N_u}}{\mathrm{V_u}} \right) \qquad (9)$$

where BRN is the Blade Rotation Number (1/m), ΣM the total number of mixing blades, N_d the rotation speed of the blades during penetration (rpm), V_d the mixing blade penetration velocity (m/min), N_u the rotational speed of the blades during withdrawal (rpm) and V_u the mixing blade withdrawal velocity (m/min). The BRN evaluates the mixing degree. It gives the total number of mixing blades passes during 1 m of shaft movement (CDIT, 2002). A high value of BRN decreases the coefficient of variation of the DSM strength. According to Topolnicki and Pandrea (2012), the minimum required BRN depends on the soil type. For cohesive and fine grained soils (loose sands and clays) about 400 (1/m) should be achieved

to keep the coefficient of variation for the strength within acceptable limits. In non-cohesive and coarse soils slightly lower values can be sufficient.
As the BRN was introduced for soil-cement column technique, Bellato et al. (2012) propose an equivalent factor for the evaluation of the mixing degree for DSM material performed with CSM technology: the "*Mixing quality parameter*", μ, which represents an estimate of the homogeneity achieved in the CSM panel and takes into account the effect of the real soil conditions. According to Bellato et al. (2012), μ (1/m) can be defined as:

$$\mu = \left[\left(\varphi_d R_{d,i} T_{d,i}\right) + \left(R_{u,i} T_{u,i}\right)\right] \frac{N_c M}{100 V_c} \tag{10}$$

where $R_{d,i}$ and $R_{u,i}$ are the average rotational speed of the mixing wheels during the penetration and the withdrawal phase, respectively. $T_{d,i}$ and $T_{u,i}$ are the total time taken to blend the soil during the downstroke and the upstroke, respectively. N_c is the number of mixing wheels (2 for the CSM machine). M is the number of mixing element per wheel and V_c the volume occupied by the cutter. All quantities with the subscript "i" are referred to a single i^{th} layer of predefined thickness. φ_d is called phase factor and takes into account the different role played by the executive procedure adopted for the realization of the panel, i.e. one phase ($\varphi_d = 1$) or two phases system ($\varphi_d = 0.5$).
Indeed, as explained in Gerressen and Vohs (2012), deep mixing with CSM can be performed in one phase mixing procedure (for applications less than 15m deep in relatively soft ground) or with a two phase system (when mixing deeper panels or penetrating difficult – slow – to mix soils or rocks). In the one phase procedure, the final mixture product consists of cement and water (and possibly bentonite), which is injected on both the down stroke and the upstroke of the machine. In the two phase procedure, just bentonite is used on the down stroke. Once the final depth is achieved, the water/binder mixture is introduced and mixed on the upstroke. This method prevents the mixing tool from being trapped in the panel if the panel construction time exceeds the initial set time of the water/binder mixture.

3.3.2. Influence of the cement content

As the degree of mixing is the governing factor of the homogeneity of the DSM material, its strength is mainly related to the amount of cement (or binder) introduced during the mixing process. According to Maswoswe (2001), the critical factor in the execution of DSM structures is to maintain the auger withdrawal rate consistent with the grout flow rate. One way to evaluate the success of the procedure and its efficiency is to estimate the cement factor or cement content (the cement mass per cubic meter of DSM material) at different locations. On the one hand, the cement factor can be estimated considering the grout flow rate, the auger withdrawal rate and the assumed percentage of grout loss during the process. On the other hand, the cement content is directly related to the water/cement factor, w/c, (or water/binder factor, w/b) of the injected mixture.
Bellato et al. (2012) propose a procedure for the estimation of the UCS at 28 days of curing with regard to the amount of injected cement. Their approach takes into account the fine content (FC), the mixing quality parameter (μ) and if necessary the effects of the *pH* on the UCS of the DSM material.

3.3.3. Influence of curing conditions

According to Bellato et al. (2012), several relationships are developed in the past to take into account the effect of the curing time on the strength development of concrete, such as those based on linear and double hyperbolic equations, exponential and logarithmic functions. Bellato et al. (2012) tried to fit their experimental data of CSM treated overconsolidated clays to these empirical relationships, but with unsatisfactory results except the case of the formula provided by EN 1992-1-1 (Ganne et al., 2010):

$$UCS(t) = \beta_{cc}(t)\, UCS_{28days} \tag{11}$$

where UCS(t) expresses the evolution of the strength with the time, t is the time and UCS_{28days} the UCS value at 28 days of curing time. β_{cc} is defined as:

$$\beta_{cc}(t) = \exp\left(s\left(1 - \sqrt{\frac{28}{t}}\right)\right) \tag{12}$$

where s is an empirical factor mainly depending on the type of cement.
According to Bellato et al. (2012), the most satisfactory fit for a curing time larger than 3 days was found with the equation:

$$\mathrm{UCS}(t) = \ln(t) - 1 \tag{13}$$

To better represent the increase of the UCS with the curing time observed in the Bologna specimens, Bellato et al. (2012) proposed a new empirical equation, based on a double hyperbolic function. This function is composed of two terms. The first one describes the increase of the UCS in the first 28 curing days, whereas the second one defines the development of the long-term strength. This relationship is given by:

$$\mathrm{UCS}(t) = \frac{\mathrm{UCS}_{28days} \cdot t}{t + K_1 \cdot \mathrm{UCS}_{28days}} + \frac{\Delta \mathrm{UCS}_{\infty} \cdot t}{t + K_2 \cdot \Delta \mathrm{UCS}_{\infty}} \tag{14}$$

in which UCS_{28days} can be corrected to take into account the amount of injected cement, the fine content, the mixing quality parameter and the *pH*. ΔUCS_{∞} is the strength increment due to long-term reaction products. K_1 and K_2 are two constants dependent on the type of clay and cement used in the treatment (in the case of the CSM treated Bologna overconsolidated clays K_1 =1 and K_2 =100).

4. FIELD OF APPLICATIONS AND CASE HISTORIES

Originally, DMM was developed for GI applications in soft clays and organic soils. More recently, it was dedicated to various structural and environmental applications: earth/water retaining structure, foundation and soil reinforcement, land levee and slope stabilization, in situ remediation and barrier against liquefaction. The following paragraphs illustrate these applications with the help of case histories presented by authors of the Deep Mixing session.

4.1. DSM technique as excavation support: earth/water retaining structure

In recent years, DSM has increasingly been used for the retaining of soil and water in the case of excavations. As a matter of fact, soil mix walls (SMW's) represent a more economical alternative to concrete secant pile walls and even in several cases for king post walls (i.e. soldier pile walls). Rutherford et al. (2005) proposed a historical background of excavation support using SMW. They also compared SMW with usual types of excavation support and with other GI techniques used for retaining wall construction.
The DSM cylindrical columns or rectangular panels can be placed next to each other, in a secant way. By overlapping the different DSM elements, a continuous SMW is realized. Steel H- or I-beams are inserted into the fresh DSM material to resist the shear forces and bending moments. The maximum installation depth of the SMW lies – so far – in the order of 25 m. The main structural difference between SMW and the more traditional secant pile walls is the constitutive soil mix material instead of traditional concrete.

In the present symposium, several papers report case histories related to permanent or temporary earth/water retaining structures. Table 4 summarizes these papers with regard to the DSM function (water and/or earth retaining structure), the temporary or permanent character of the construction, the type of soil, the localization of the project and their content.

Peixoto et al. (2012a) describe the construction of a retaining wall designed to allow the excavation of the underground floors of a new building block near existing buildings. The main challenge of this project consisted in the execution of an urban excavation with an average depth of 9 m under demanding ground and water table conditions. The design of the retaining wall had to guarantee minimum interference with the surrounding area, the security during and after the works (long term study) and the reduction of the water inflow into the excavation. In this context, a SMW was designed and performed with the help of CSM panels (see Fig. 13). The SMW was reinforced by vertical IPE 450 steel profiles and horizontally supported by two levels of horizontal struts in order to limit disturbance of the surrounding area and to use the SMW as foundation element of the internal structure. According to the surrounding conditions, horizontal displacements were limited to 5 mm at the top of the SMW and 20 mm along its height for design consideration. The analysis of the SMW was carried out using the Finite Element Method (FEM) program PLAXIS® with acceptable results.

The paper of Peixoto et al. (2012b) concerns the construction of a temporary SMW for the excavation of an underground parking lot. The solution consisted in a CSM retaining structure ensuring the stability of the nearby infrastructures and reducing the inflow of water into the excavation during the construction phase. The CSM panels were reinforced by vertical IPE 330 steel profiles and one level of ground anchors was performed in the top of the wall, as illustrated in Fig. 14.

Table 4: Summary of the papers concerning SMW with earth/water retaining functions

Papers	**DSM function and duration**	**Type of soil**	**Contents**
Peixoto et al. (2012a) *Permanent Excavation Support in Urban Area using Cutter Soil Mixing technology at Cannes, France*	Permanent excavation support, permanent foundation and water retaining applications with CSM	Stratified soil: clayey and silty fill, sandy clays and bedrock (sandstone)	Description of the design of the solution and numerical modeling with Finite Element Method FEM (Plaxis®) Execution details, QC aspects (UCS on wet grab samples) and monitoring plan (surveying targets, inclinometers and extensometers in the struts)
Peixoto et al. (2012b) *The application of Cutter Soil Mixing to an urban excavation at the riverside of Lagos, Portugal*	Temporary earth/water retaining wall for excavation with CSM	Sandy fill and calcarenite substratum	Description of the CSM technique, the design and the execution of the solution QC aspects (UCS, modulus of elasticity (E) and tensile splitting strength (T) tests on 36 wet grab samples) and monitoring plan (5 inclinometers, 5 load cells and 17 surveying targets)
Peixoto et al. (2012c) *Earth Retaining Structure using Cutter Soil Mixing technology for the "Villa Paradisio" Project at Cannes, France*	Temporary earth/ water retaining wall for excavation with CSM	Clayey fills and fractured dolomitic rock	General description of CSM technique Details of the design and execution of the solution and FEM of the retaining wall with Plaxis®
Peixoto et al. (2012d) *Solution of earth retaining structure using Cutter Soil Mixing technology: "Parking Saint Nicolas" Project at Cannes, France*	Temporary earth/water retaining wall with CSM	Sandy clay overlying substratum of marls	Details of the design and execution process and FEM of the retaining wall with Plaxis® QC aspects (UCS tests on wet grab samples) and monitoring plan (19 survey targets and 3 inclinometers)
Pinto et al. (2012) *Ground Improvement Solutions using CSM Technology*	Temporary circular shaft for excavation below ground water table at Ponte de Lima (Portugal)	Heterogeneous soil: heterogeneous landfills, sandy and gravel soils and weathered schist	General description of CSM technique Different case histories with CSM: design/execution criteria for foundation, slope stabilization and temporary or permanent earth retaining structures above and below ground water table QA/QC aspects (UCS and E tests on core samples) and monitoring plan
	Permanent earth retaining wall for excavation in Lisbon (Portugal) with geodrains for the control of the water table	Heterogeneous soil: heterogeneous landfills and Miocene medium dense to dense sands and sandstones	
	Permanent earth/water retaining wall and foundation solution in Lisbon (Portugal)	Heterogeneous soil (heterogeneous landfills and alluvial muddy soils, located over the Miocene very stiff clays) with the water table up to ground level	

Figure 13: View of the excavation after the execution of the second level of struts, after Peixoto et al. (2012a)

Figure 14: View of the excavation, after Peixoto et al. (2012b)

Peixoto et al. (2012c) present the design and execution aspects of a SMW performed for the construction of the underground floors of "Villa Paradisio", at Cannes, France. The building was located in a densely built-up area and bounded by streets, buildings and an old concrete pipeline. This urban excavation presented a maximum depth of 12 m. The ground water level was situated halfway up the excavation. The presence of dolomitic bedrock, under the clayey fills, constituted a good support for the bottom of the SMW, allowing the design of a safe solution with only one level of horizontal steel pipe struts, as illustrated in Fig. 15. The SMW consisted in a continuous CSM wall. The minimum length of the CSM panels was 15 m ensuring a minimum penetration of 3 m into the bedrock. The CSM wall was reinforced with the help of IPE 450 steel profiles. A concrete beam was executed at the top of the SMW to connect the vertical steel piles. According to the surrounding conditions, horizontal displacements were limited to 15 mm at the top of the SMW and 25 mm along its height. Once again, the analysis of the SMW was carried out using the FEM program PLAXIS® with acceptable results.

Figure 15: View of the SMW with the steel waler beams, the internal struts and the concrete wall, after Peixoto et al. (2012c)

Peixoto et al. (2012d) present the design and execution aspects of a retaining structure for the construction of an underground parking lot. The retaining wall for the construction of the four underground floors was executed with the help of CSM panels reinforced with vertical IPE steel profiles. The depth of the excavation rose up to 14 m. The SMW was horizontally supported by two levels of reinforced concrete slab bands rigidified and supported by temporary micropiles, as illustrated in Fig. 16. The excavation was once again located in an urban zone and bounded by streets and buildings. The performance of the retaining wall was evaluated using the FEM program PLAXIS®. All the execution phases were modeled. The analysis included the determination of the maximum values for the strength and displacements of the SMW.

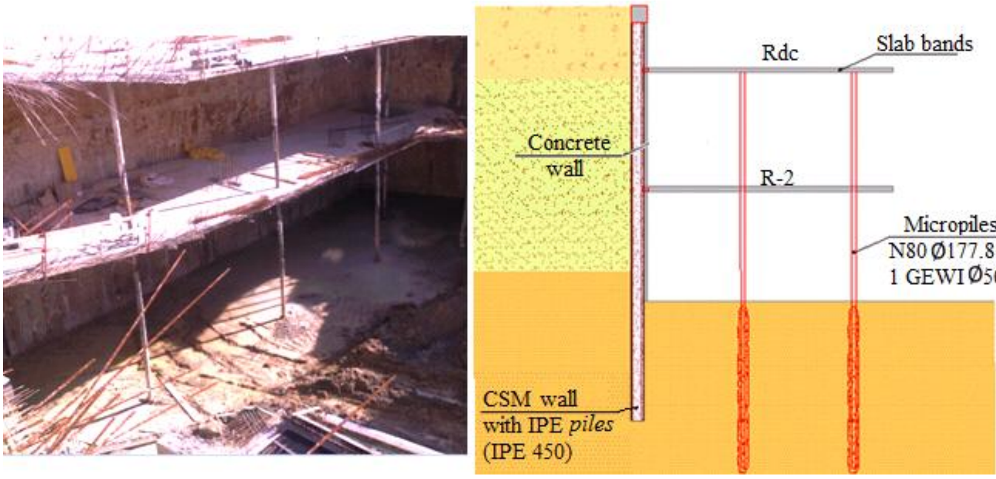

Figure 16: Partial view of the excavation (on the left) and cross-section of the retaining wall (on the right), after Peixoto et al. (2012d)

Pinto et al. (2012) first present an example of the CSM technique applied for the construction of two shafts with earth and water retaining function. Those shafts with about 18 m depth and 15 m diameter were built in order to allow the installation of a water supply pipe, under the river using micro tunneling technology. The CSM panels were built with an overall depth of 24 m and reinforced with vertical IPE300 steel profiles. The CSM panels were designed to transmit horizontally the earth and water pressures to the vertical profiles. The profiles were braced, at the top, by a reinforced concrete capping beam and by three lower levels of steel ring beams, as illustrated in Fig. 17. For the design, a 2D FEM axisymmetric model was adopted using Plaxis® software.

Figure 17: Inside view of the right bank shaft after excavation, after Pinto et al. (2012)

In the following, Pinto et al. (2012) concentrate on an earth retaining solution for the enlargement of a railway platform, in order to accommodate the new infrastructures of High Speed train in Lisbon. The maximum depth of the excavation was 13 m. CSM panels were executed with maximum depth of 18 m and reinforced with the help of IPE240 hot rolled steel profiles. The CSM panels were designed in order to be integrated with the final earth retaining solution and in such a way to limit the water inflow in the excavation. For the design, FEM analysis was carried out using Plaxis® software. Figure 18 respectively presents the excavation works and the designed solution.

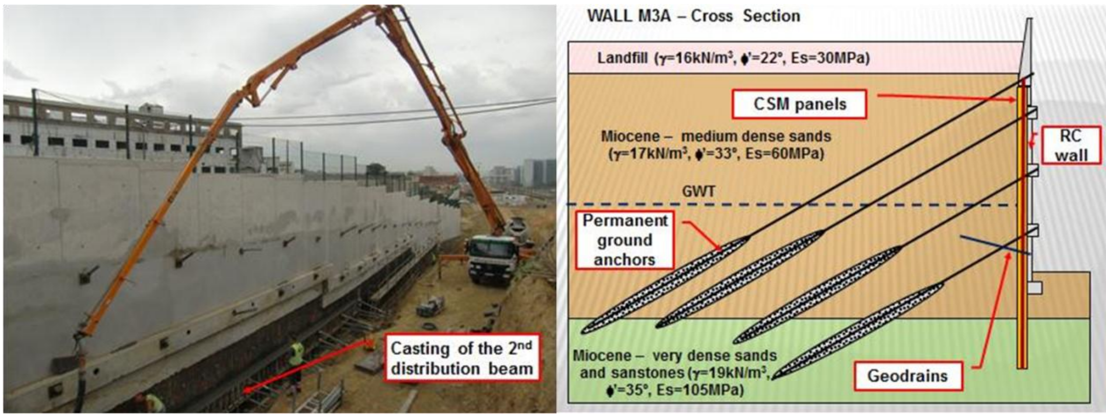

Figure 18: Excavation works (on the left) and cross section of the adopted solution with geological conditions (on the right), after Pinto et al. (2012)

Finally, Pinto et al. (2012) give the details of an earth/water retaining and foundation structure realized for the construction of a pumping station. The depth of the excavation was 12m. CSM panels with an overall depth of about 24 m were performed and reinforced with vertical IPE300 hot rolled steel profiles in order to resist to the structural loads, the earth and water pressures, and to limit the deformations. Buttress panels were also built in order to increase the earth retaining structure overall stiffness, as illustrated in Fig. 19. The CSM panels were designed in order to be integrated with the final foundation and earth retaining solution and to limit the water inflow into the excavation. For the design, 2D FEM analysis were carried out using Plaxis® software.

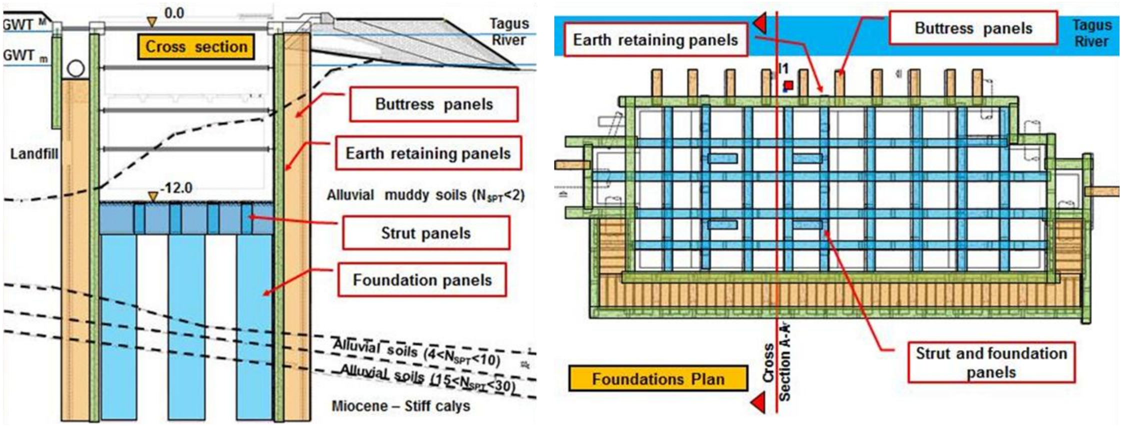

Figure 19: Cross section (on the left) and plan of the adopted solution (on the right), after Pinto et al. (2012)

4.2. DSM technique for foundation applications and soil reinforcement

Since several years, there is an increasing need of establishing new constructions on soils of poor quality and especially in alluvial area. That need resulted in the developments of new suitable and sustainable GI and foundation solutions with special attention with regard to the execution time and economic questions. In this respect, DMM constitutes an interesting alternative to the traditional foundation solutions, with some technical, economic and environmental advantages.

In the present symposium, several papers report case histories related to permanent use of DSM material for foundation applications. Table 5 summarizes these papers with regard to the DSM function, the type of soil, the localization of the project and their content.

Chapman et al. (2012) present GI works performed to found a liquefied natural gas (LNG) tank with 85 m diameter and 54 m high on tidal mangrove mud flats which have been reclaimed using dredged spoil. The traditional engineering solution for this type of site is to use deep foundation (piles). However, this solution was found to be excessively expensive. Hence, the solution consisted in a granular load transfer layer placed over the top of CSM panels. The design comprised 605 CSM panels with depths varying between 13 and 15 m below the bottom of the proposed load transfer layer. Figure 20 illustrates the soil layering below the tank and the CSM panel layout.

Table 5: Summary of the papers concerning DSM technique for foundation applications

Papers	**DSM function**	**Type of soil**	**Contents**
Chapman et al. (2012) *Ground Improvement works for an LNG storage tank foundation*	GI with CSM for permanent foundation of a liquefied natural gas (LNG) tank in Coast of North Queensland	Tidal mangrove mud flats (dredged spoil)	Details of the design of CSM foundation Description of laboratory UCS tests on wet grab samples and mention of plate load tests 2D plane strain and axisymmetric 2D analyses with Plaxis®
Mendes et al. (2012) *Assessing the feasibility of a foundation treatment solution based on CSM panels at a river dock in Lisbon*	CSM panels for permanent foundation of buildings	Landfill (soft soils)	Laboratory test campaign on mixture specimens (to determine the cement, organic matter and sulphates contents): water content, small strain stiffness (P wave velocity propagation tests), UCS, E, T and shear strength (CU TX) tests Effect of curing (14, 28, 54 and 91 days) Quality index for sample selection
Peixoto et al. (2012e) *Solutions for soil foundation improvement of an industrial building using Cutter Soil Mixing technology at Fréjus, France*	CSM for permanent GI application: foundation of an industrial building	1 m thick layer of predominantly gravelly fills, 2-6 m thick layer of colluvial soils with low strength and deformability over a marl-sandstone substrate	Description of the design and numerical modeling with FEM (Plaxis®) Details of the execution process and QA/QC aspects (UCS on wet grab samples)
Pinto et al. (2012) *Ground Improvement Solutions using CSM Technology*	Permanent foundation solution in Lisbon	Landfill with demolishing waste, alluvial soft soils and Miocene bed rock	Description of the design and execution criteria for foundation below ground water table QA/QC aspects (UCS and E tests on core samples) and monitoring of the building during and after construction
Lambert et al. (2012) *Soil-cement columns, an alternative soil improvement method*	Soil reinforcement for railway infrastructure with soil-cement columns performed with the help of the FLAPWINGS® tool (Keller Foundations)	Silty soil	Description of the European Research Project INNOTRACK (2006-2009) Details of the execution, the excavation, the field load tests on 2 columns and the laboratory tests on core samples Comparison with Jet grouting
Guimond-Barrett et al. (2012a) *Deep mixing for reinforcement of railway platforms with a spreadable tool*	Reinforcement and re-use of railway platforms and existing foundations with the help of soil-cement columns executed with the SPRINGSOL® tool (Soletanche-Bachy)	Stratified soil: fill, clay/silt and gravelly sand	Description of the Rufex project Details of the execution and QC aspects with the excavation of the columns and the laboratory tests on cores
Dhaybi et al. (2012) *Foundations reinforced by soil mixing: Physical and numerical approach*	Shallow foundations on DSM columns	Hostun sand	Reduced scale modeling and axisymmetric FEM of shallow foundations on soil-cement columns
Suganya et al. (2012) *Parametric study of embankments founded on soft organic clay using numerical simulations*	Embankments founded on soil-cement columns	Soft organic clay	Parametric study of embankments founded on soil-cement columns for the reinforcement of soft organic clay using FDM with FLAC 2D®: influence of the column properties, spacing, area, mass stabilized zone and pile material modeling

The optimization of the DSM material was conducted through laboratory and trial panel tests. 2D plane strain and axisymmetric 2D analyses were carried out using the FEM Plaxis 2D® program. The analyses were carried out to estimate the long term settlement as well as the variation of the normal stresses and the coefficients of subgrade reaction.

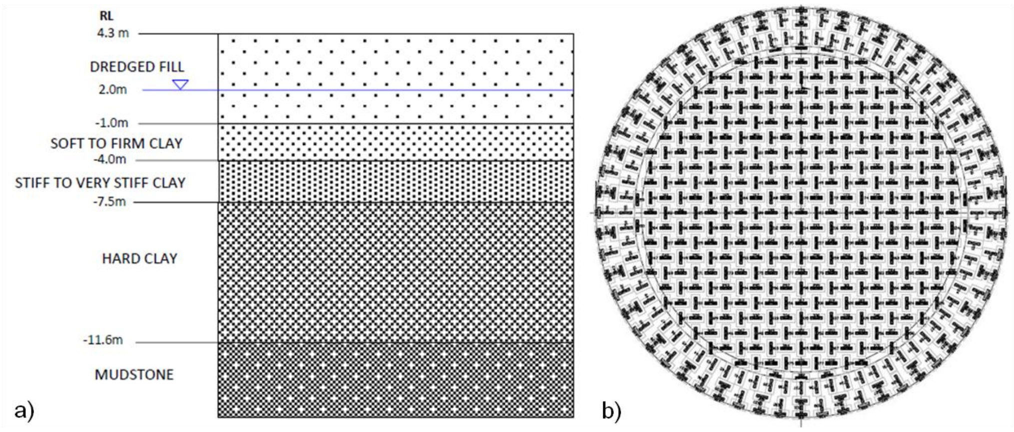

Figure 20: a) Soil layering below the LNG tank and b) CSM panel layout, after Chapman, et al. (2012)

Mendes et al. (2012) discuss the construction of an embankment on CSM panels within the framework of a project of soil reinforcement of a reclamation area in Lisbon (Portugal). The design consisted in a load transfer platform (geosynthetics and landfill) installed on the top of CSM panels. Despite the use of several cement contents, the UCS of wet grab and core samples remained below the minimum required UCS value. A method based on X-ray fluorescence was implemented to determine the real cement content of the CSM test panels. Figure 21a presents the measured cement content with regard to the nominal cement content injected in the panels. On the basis of these results, it can be concluded that the low UCS values were partly due to a deficient soil-cement mixture. That was confirmed by the visual quality of the core specimens (see Fig. 21b). Next, the increase of the UCS with time was studied. It must be noted that in the case of this project, organic and sulfate contents were observed in the field. The presence of organic matter in the mix restrains the cement hydration. If pozzolanic cement was used to reduce, yet not avoid, the sulfate attack, it is still expected that sulfates influence the mechanical behavior of soil-cement panels in the long term, as demonstrated in Guimond-Barrett et al. (2012b).

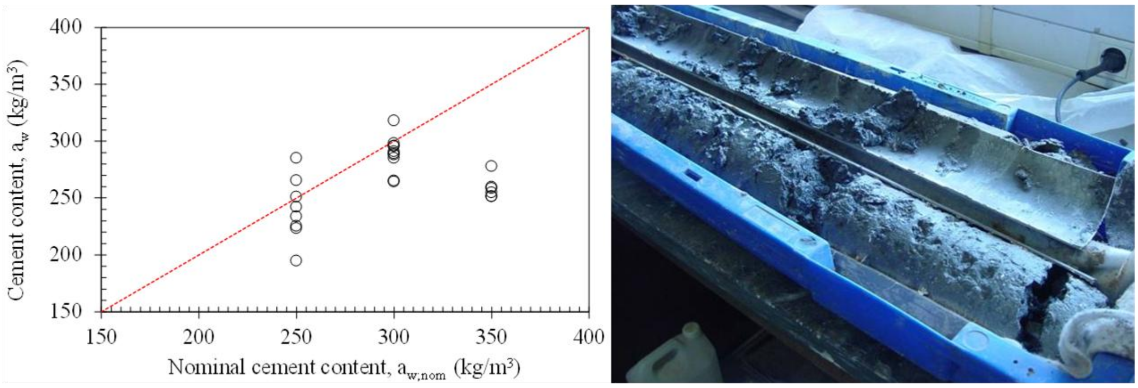

Figure 21: (a - Left) Measured cement content versus nominal cement content injected in the CSM panels. (b - Right) Core samples from the CSM test panels, after Mendes et al. (2012)

Peixoto et al. (2012e) describe the 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 marl-sandstone substrate, detected at a depth varying between 3 and 7 m. As illustrated in Fig. 22a, an 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 22b 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 performed, upon which the concrete bottom slab of the building was placed. The analysis of the solution in terms of long-term settlements was carried out using the FEM Plaxis® program.

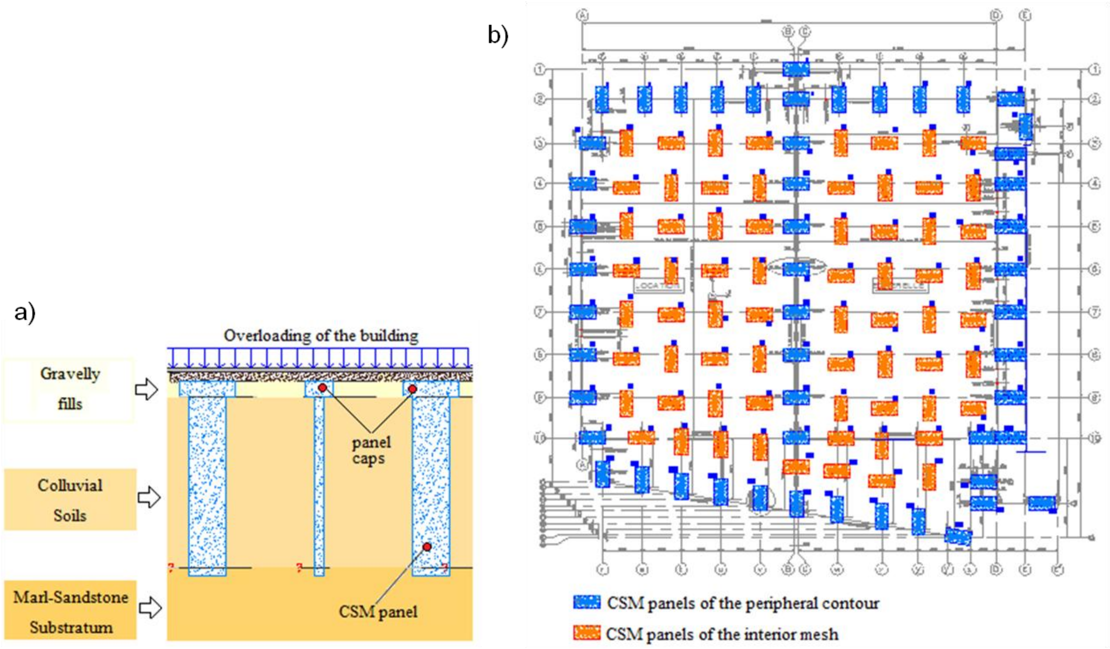

Figure 22: a) Cross section of the performed solution and b) plan view of the CSM panel distribution, after Peixoto et al. (2012e)

Pinto et al. (2012) present a foundation solution based on the CSM technique for the construction of the "Pedro Arrupe Scholl", in Lisbon (Portugal). CSM panels were executed with a maximum depth of about 25 m and reinforced with vertical HEB steel profiles. The profiles were capped by reinforced concrete caps, braced by a network of beams. As illustrated in Fig. 23, the CSM panels were designed in order to transmit the building loads to the Miocene bed rock and to resist to seismic loads.

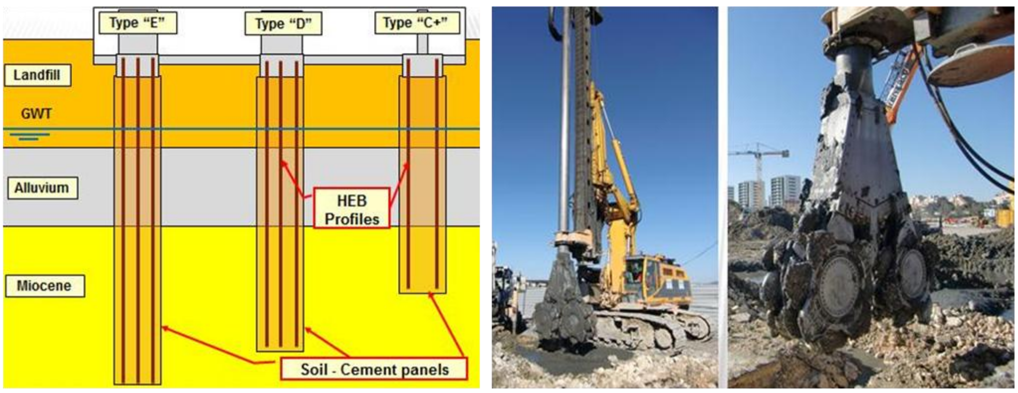

Figure 23: Cross section of the performed solutions (on the left) and execution of the CSM panels (on the right), after Pinto et al. (2012)

In order to reduce the life cycle cost of railway infrastructure, much research was performed on the track support structure. As reported in Lambert et al. (2012), development and implementation of several subgrade improvement methods allowing limited traffic interruption and privileging use of local material were the core activities of the European research project INNOTRACK (INNOvative TRACK system 2006-2009). The technique proposed by the SNCF/KELLER/IFSTTAR was ground reinforcement with vertical soil-cement columns. Lambert et al. (2012) discuss some experiments on soil-cement columns mixed by the FLAPWINGS® tool (see Fig. 3) within the framework of the INNOTRACK project. The FLAPWINGS® tool is presented in paragraph 2.1.3 of the present General Report. The device meets the execution requirements in a railway environment, but other applications are also possible. The technique only requires a small drilling machine and can thus be applied in difficult accessible field areas. Another advantage is that the drilling can be protected by steel tubes in order to avoid grout pollution of the top layers like ballast of railways. Lambert et al. (2012) discuss static load tests (SLT's) on two columns with 600 mm diameter and instrumented with the French removable extensometer (see Fig. 24a and b). The

influence of the water/cement, w/c, ratio and the effect of the cement density have been studied. It was shown that 70% of the load was taken by the shaft and 30% by the tip of the column.
Finally, it was observed that the mechanical behavior of the soil-cement column is comparable to jet grouting inclusions in terms of UCS resistance for similar soils and similar cement contents.

a) b)

Figure 24: a) View of an excavated column with diameter about 640 mm and b) view of the load test system, after Lambert et al. (2012)

Subsequently to the INNOTRACK project, the RUFEX project, which started in 2010, focuses on the reinforcement and re-use of existing railway tracks and on the DSM technique for foundation application. Its main objectives are to investigate the behavior of DSM structures with the study of the tools and binder compositions and to focus on the design aspects of wet soil mix. Guimond-Barrett et al. (2012a) present results of field tests carried out as part of the RUFEX project. They study the installation of soil-cement columns of 400 mm and 600 mm diameters constructed under existing railway lines without removing the tracks. Soil mixing is performed by the Springsol® mixing tool (see Fig. 4 and paragraph 2.1.4). In its folded configuration, the tool diameter is 160 mm enabling its insertion into a temporary casing to protect railway ballast from grout pollution (see Fig. 25). Once it reaches the end of the casing and penetrates the underlying soil, the blades spread out and the mixing operation begins. Two sets of columns were respectively installed under an existing and under a planned track. Two other sets were installed to be excavated and for SLT's. Penetration and rotation speed were varied for investigation purposes.

Figure 25: Installation procedure for soil-cement columns under existing tracks, after Guimond-Barrett et al. (2012a)

Dhaybi et al. (2012) discuss the behavior of shallow foundations reinforced by soil-cement columns and mechanisms of composite interface. This is done on the basis of physical and numerical models. For the physical model, an experimental setup is constructed in a tank with dimensions of 2×1×1 m³, as illustrated in Fig. 26. The soil-cement column is installed by sinking a steel tube in the sandy soil, emptying it and filling up with a laboratory mixture. A rigid steel plate is placed on the top of the column for the loading. Three tests are conducted: one without column and two with soil-cement column at 7 and 14 curing days. Apart from the physical model, an identical setup is simulated in ABAQUS by an axisymmetric FEM model calibrated with the experimental results. The numerical simulations show a good agreement with the physical modeling in cases of axial stresses, displacements and failure mode.

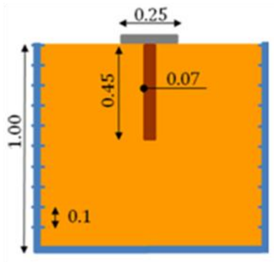

Figure 26: a) Experimental setup and b) schematic cross section of this setup, after Dhaybi et al. (2012)

Suganya and Sivapullaiah (2012) describe a similar study of soil-cement columns as Dhaybi et al. (2012). In this case, embankments are founded on soft organic clay ground which is reinforced with soil-cement columns to enhance bearing capacity and reduce settlements (see Fig. 27). The extent of improvement in stability and settlement characteristics of embankments mainly depends on the properties of the soil-cement columns, the column spacing and the column diameter. Suganya and Sivapullaiah (2012) investigate these factors through simulations based on the 2D finite difference method using FLAC 2D®. The simulations show clearly how the soil-cement columns reduce the settlements and horizontal displacements and how they increase the safety factor. A lower w/c ratio of the soil-cement columns (and thus higher shear strength) improves the stability and settlement characteristics of the embankment foundation. It is also observed that a sodium silicate (NaSi) additive considerably improves the column strength characteristics, but its effect on the safety factor and settlements is less significant. Finally, decreasing column spacing and increasing column area reduce settlements and horizontal displacements. Suganya and Sivapullaiah (2012) provide information on bearing capacity, settlements and global stability of embankments founded on soil-cement columns. In the same framework, the following paragraph concentrates on this application with the help of two history cases.

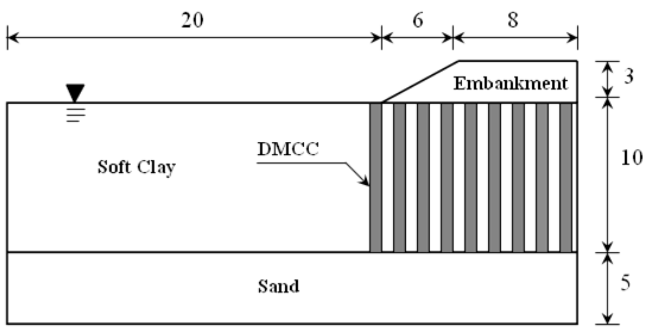

Figure 27: Embankment on soil-cement columns, after Suganya and Sivapullaiah (2012)

4.3. DSM technique for land levee

In the present symposium, two papers report case histories related to permanent use of DSM material for foundation of land levee projects, both in New Orleans. Indeed, the effects of Hurricane Katrina which passed southeast of New Orleans on August 29, 2005, have been long-lasting. The storm caused more than 50 breaches in drainage canal levees and also in navigational canal levees and precipitated one of the worst engineering disasters in the history of the United States of America. In response, construction and reconstruction of levee were planned; in several cases, with the help of the DSM technique. Table 6 summarizes these papers with regard to the DSM function, the type of soil and their content.

The LPV111 project (Leoni and Bertero, 2012) consisted in the raising of an existing 8.5 kilometer levee, which rests on a foundation of soft organic clay. LPV111 is part of the New Orleans East Back Levee, which is an essential component of the New Orleans Hurricane Protection System. DMM was selected to stabilize and support the burden of the new levee, as illustrated in Fig. 28. 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.

Table 6: Summary of the papers concerning DSM technique for foundation and stabilization of land levee

Papers	**DSM function**	**Type of soil**	**Contents**
Leoni and Bertero (2012) *Soil mixing in highly organic materials: the experience of LPV111, New Orleans, Louisiana (USA)*	DMM applied for permanent foundation and stabilization of a land levee (LPV111 project) with the help of the TTM single, TTM double and CI-CMC double systems	Existing levee fill, soft clay, marsh/peat deposits, fat clay, and Pleistocene soils	General description of the project Preliminary laboratory program: Bench-scale test with the study of the effect of the w/c ratio, the type and the amount of cement on the UCS Field test program (Validation tests) QA/QC testing (5000 cores with UCS tests) and UCS design consideration
Mc Guire et al. (2012) *Stability Analyses of a Floodwall with Deep-Mixed Ground Improvement at Orleans Avenue Canal, New Orleans (USA)*	Dry Deep Mixing method for the permanent stabilization of a section of a land levee and floodwall	Clays and cohesionless soils	Numerical analysis of the stability of a section of a land levee and floodwall with the finite difference method and a limit equilibrium analysis (using Spencer's method) Study of the influence of vertical joints in the deep-mixed zone and study of the influence of a water-filled gap on the flood side of the cantilevered floodwall

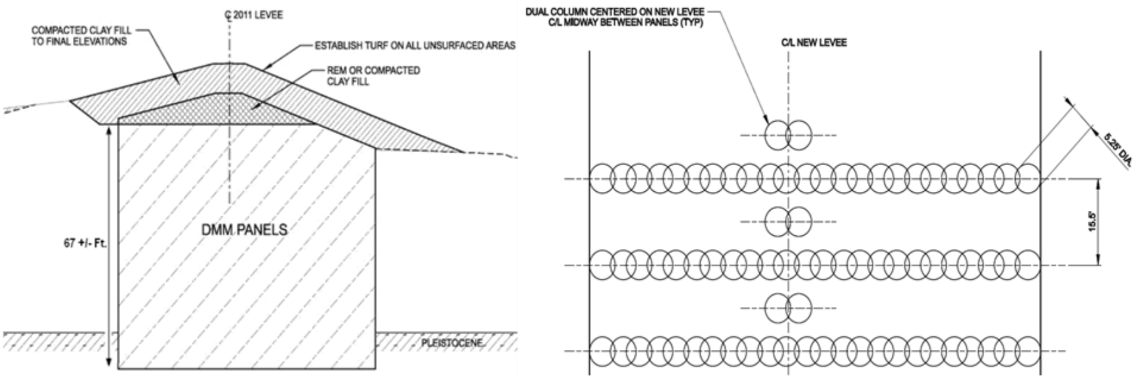

Figure 28: Typical design of DMM stabilization at LPV111 (cross section & plan view), after Leoni and Bertero (2012)

In New Orleans, dry deep mixing was used to improve the stability of a section of the land levee and floodwall along Orleans Avenue Canal. McGuire et al. (2012) studied the stability of this construction with the help of the finite difference method (using FLAC® program) and the limit equilibrium analysis (using the Spencer's method). The influence of the following parameters on the stability was taken into account in the analysis:

- the presence of vertical joints in the deep-mixed zone,
- the emergence of a water-filled gap on the flood side of the floodwall,
- and the potential water-filled tension cracks in the ground on the flood side of the floodwall.

The influence of joint efficiency was investigated by performing FLAC® analyses. It was shown to be very small with and without a water-filled gap. The influence of the water-filled gap on the safety factor was more significant than the influence of vertical joints. The shear strain contours at failure for both analyses (including or not a gap) are similar. They are shown in Fig. 29 and indicate a global failure mode.

Limit equilibrium analyses were also performed for the analysis of the cross section of the levee. The safety factors calculated using FLAC® and Spencer's method without a tension crack are within 5% for all comparable cases. As illustrated in Fig. 29, the primary mode of failure in the FLAC® analyses is global rotation and translation of the levee and I-Wall with shearing through the DMM zone. This mode of failure is also captured by the limit equilibrium analyses. The presence of a water-filled gap adjacent to the sheet piles produces a decrease of about 2 to 5% in the calculated factor of safety, depending on the analysis method.

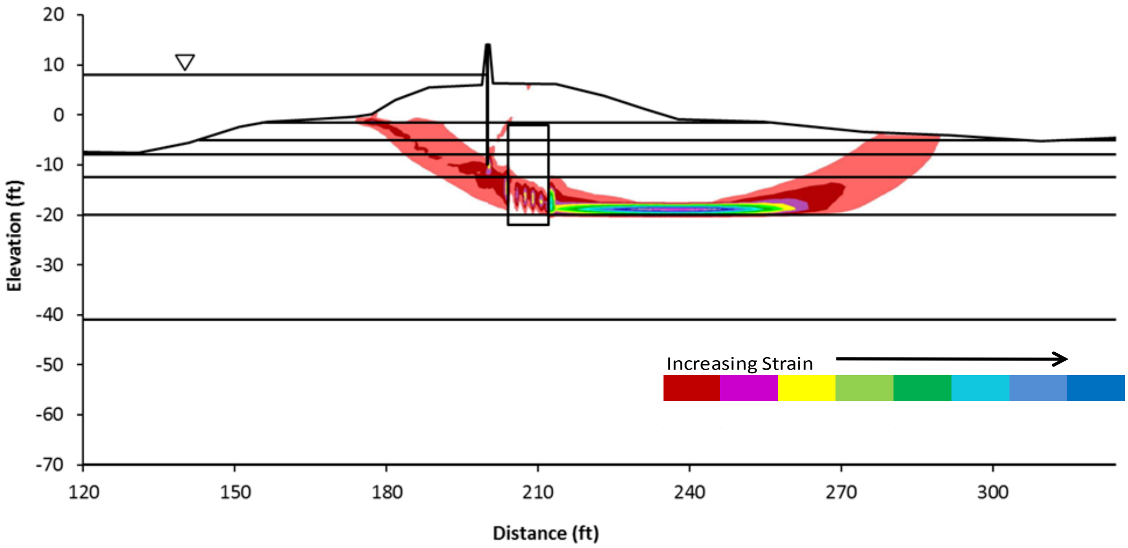

Figure 29: Example of shear strain contours for the numerical stability analyses performed without a water-filled gap and with 0% joint efficiency, after McGuire et al. (2012)

4.4. DSM technique for slope stabilization

Another application area of the DSM technique is slope stabilization. Pinto et al. (2012) and Gaib et al. (2012) both present a case history of this type of application. Table 7 summarizes these papers with regard to the DSM function, the type of soil and their content.

Table 7: Summary of the papers concerning DSM technique for slope stabilization

Papers	**DSM function**	**Type of soil**	**Contents**
Pinto et al. (2012) *Ground Improvement Solutions using CSM Technology*	Permanent slope stabilization and foundation in Amarante (Portugal)	Heterogeneous landfills located over weathered granite	Description of the design and construction 2D analyses using Slide® and Plaxis® softwares for the evaluation of the overall stability for static and seismic loads
Gaib et al. (2012) *Design, Construction and Monitoring of a Test Section for the stabilization of an Active Slide Area utilizing Soil Mixed Shear Keys installed using Cutter Soil Mixing*	CSM for permanent slope stabilization in British Colombia (Canada): DSM shear keys	Post glacial earthflow: poorly lithified tertiary sediments dominated by shale, mudstone, or clay	Stability analysis with the limit equilibrium slope stability program SLIDE 5.0 Description of the design solution General description of DSM and CSM technologies Design of field trial sections and strength selection Field implementation and QA/QC aspects with regard to the UCS tests on wet grab and core samples at different time and to the monitoring plan (during execution and after stabilization with the help of inclinometers, surveying targets and LIDAR – Light Detection And Ranging – measurements)

The case history described by Pinto et al. (2012) concerns the widening of an existing road platform (indicated by IP4 in Fig. 30) near the city of Amarante in Portugal. CSM panels were installed for slope stabilization of the heterogeneous landfills that were used for the construction of the existing road platform. A cross section of the geological conditions and the adopted solution with CSM panels is shown in Fig. 30. CSM panels also serve as foundation for the wall self-weight (maximum height is about 20 m) and the motorway traffic with the help of a load transfer platform (LTP). For the design, 2D analyses were carried out using Slide® and Plaxis® softwares in order to evaluate the overall stability for static and seismic loads.

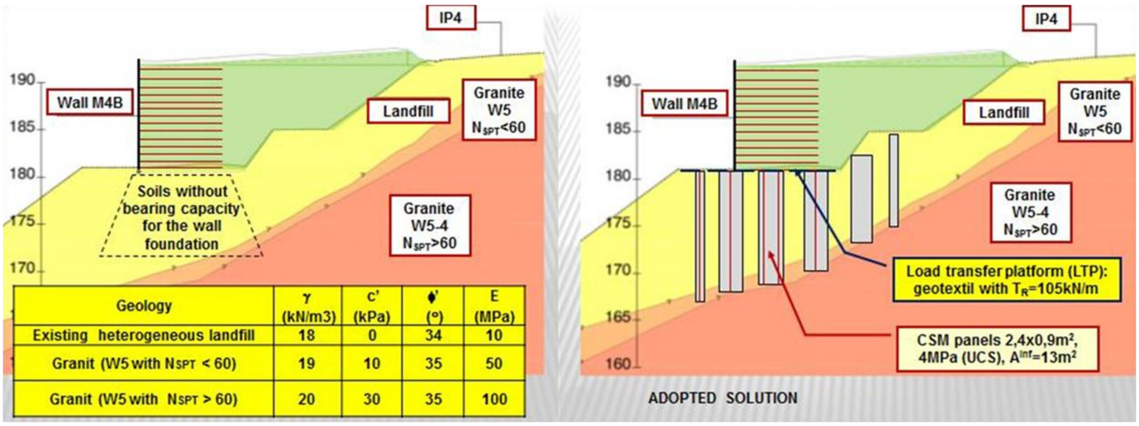

Figure 30: Cross section of the geological conditions and adopted solution, after Pinto et al. (2012)

Gaib et al. (2012) describe another example of the use of CSM panels for slope stabilization. The "Fountain Slide" has been active for decades and it is part of a massive postglacial earthflow known as the Tunnel Earthflow in British Colombia in Canada (see Fig. 31). The estimated landslide volume is 750 000 m³. Since 2009, movement rates have reached an average value of 5 mm/day, with observations up to 10 mm/day. As a result, significant ongoing maintenance of the highway has been required and investigation of stabilization options was need. Slide analysis was carried out using the limit equilibrium slope stability program Slide 5.0®. The chosen alternative was the use of the CSM technique to develop in-situ shear keys across the sliding area. In order to evaluate this approach, a trial section consisting of a number of subsurface shear walls, or barrettes, across the eastern end of the active slide area was proposed. A total of 20 barrettes, approximately 8 m long and each made up of 3 individual panels was constructed with an orientation perpendicular to the slide. Gaib et al. (2012) discuss the design approach, the monitoring and the problems encountered during the execution. Though monitoring and observation of the slope is still ongoing, the test section has already demonstrated that the installation of CSM shear keys through the failure horizon is technically feasible and allows the decrease of the slope movements.

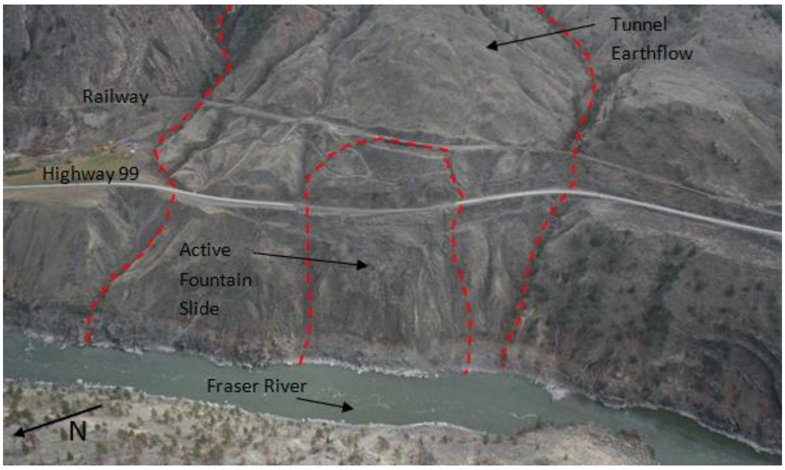

Figure 31: Aerial view of Tunnel Earthflow and Fountain Slide, after Gaib et al. (2012)

4.5. Soil Mix Remediation Technology

The in-situ remediation of contaminated land applying the DSM technique involves the use of mixing tools and additives to construct permeable reactive in-ground barriers (PRB) and low-permeability containment walls. As described in Al-Tabbaa et al. (2012), PRB walls 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, low permeability containment walls are cut-off low permeability walls designed to isolate a contaminated area from the surrounding area. Apart from these remediation techniques, the DSM technique can also be used for 'hot-spot' soil treatment by stabilization/solidification (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 (Al-Tabbaa et al., 2012).

Soil Mix Remediation is a cost-effective and versatile approach, with numerous technical and environmental advantages including the use of simple and well-established techniques, speedy implementation, applicability to sites of any size and to multiple contaminants, elimination of off-site disposal as well as low risk and low emissions. Water and soil contaminations consisting of heavy metals and/or organic contamination can be treated. This, combined with recent innovations in DSM equipment, treatments and materials, makes the DSM technology a promising and timely contender to lead the market place in offering a cost-effective, efficient and low risk solution to contaminated soil and groundwater remediation. All of this led in October 2008 to the start of the Soil Mix Remediation Technology (SMiRT) project in the UK (Al-Tabbaa et al., 2012).

Within the framework of this project, Al-Tabbaa et al. (2012) present the details of a large scale field trial application of DSM technology to the integrated remediation and ground improvement of a contaminated site with the use of a range of mixing tools. The influence of several parameters is studied, e.g. 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 used DSM systems and some provisional results are summarized in Al-Tabbaa et al. (2012).

4.6. DSM barrier against liquefaction

The DSM technique can also be used to prevent soil liquefaction and post-liquefaction damage caused by soil flow along the substratum slope. An example of such application is described by Benhamou and Mathieu (2012). Martinique (France) is an area particularly exposed to seismic risks. For the construction of two buildings on very soft silty/sandy alluvia, a new type of permanent foundation based on a Geomix caisson arrangement (36 × 40 m) is presented as liquefaction remediation technique. This type of DSM treatment is already used in Japan, where for example foundation piles where surrounded by a grid-type structure made of SMW's. As illustrated in Fig. 32, the arrangement consists in a grid performed with the help 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 to the external post-liquefaction soil flow. Finally, in a general way, the Geomix foundations also reduce settlements under the structure.

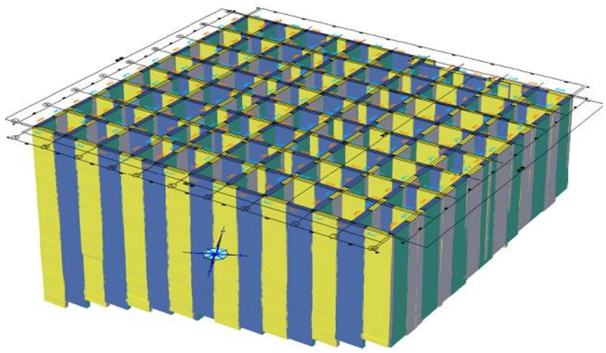

Figure 32: 3D view of the Geomix caisson structure, after Benhamou and Mathieu (2012)

5. INTERNATIONAL QA/QC PROCEDURES

5.1. QA/QC procedures and workflow of DMM project

In 2001, Maswoswe described the development and the implementation of Quality Assurance/Quality Control (QA/QC) procedures for the installation of 410 000 m³ of DSM material with the help of triple auger DSM rigs, in the framework of the Central Artery/Tunnel (CA/T) project, in Boston. At the beginning of the 90's, it was the largest land-based DSM installation in the USA, and perhaps in the world. Maswoswe (2001) related the **QC activities** to:

- the choice of the **suitable DSM equipment**,
- the determination of the **process parameters** ensuring acceptable performances: the grout mix composition, the auger rotation (or withdrawal) rate and the grout (and drilling water) flow rate,
- and the selection of **procedures** allowing auger penetration and verticality.

If the choice of the DSM equipment, the installation parameters and the procedure were left up to the contractors, specifications would require the DSM material to meet the following **acceptance criteria for QA** related to:

- the minimum and maximum values of **UCS** on samples, after a determined number of curing days,
- the verification of the **homogeneity and uniformity**,
- the minimum **unit weight** of core samples,
- the **vertical tolerance** with a limitation of the horizontal deviation with depth in any direction,
- the verification of the auger penetration and the **final depth**.

In 2011, Terashi and Kitazume have proposed a workflow for DSM projects. Their study was conducted in collaboration with experts of 45 organizations from seven countries and resulted nowadays in the relation of QA/QC activities to laboratory mix tests, field tests, monitoring and control of the execution parameters and control of the final products by measuring the mechanical characteristics of the DSM material by tests on core samples (usually UCS tests) or by sounding.
The DSM process design and the QC of DSM material, as described in Terashi and Kitazume (2011), constitutes a major schedule for the deep mixing contractors with the following steps:

- **laboratory mix test** for process design,
- **field trial installation** for confirming practicability,
- **process design** to determine final mix design and construction control values,
- **production with QC** by monitoring, control and recording the monitored data of the construction process.

In view of QA/QC development and in the context of European standardization, info sheets have been developed within the framework of the BBRI 'Soil Mix' project (Denies et al., 2012a). They consist in guidelines for execution phases and give some requirements with regard to the QC of the DSM material, the characteristic dimensions, the bearing capacity and the lateral SMW displacement. As BBRI info sheets support all QA/QC activities reported by Maswoswe (2001), they specify the QA/QC aspects in function of the DSM application (retaining wall, water barrier or foundation) and take the temporary or permanent character of the construction into account (Denies et al., 2012a).

5.2. DSM process design in practice

In the present proceedings, Leoni and Bertero (2012) describe the execution of DSM panels for land levee project LPV111 (see paragraph 4.3). The QA/QC activities related to this project follow the previous schedule with the realization of a Bench Scale Test program (BST), a Field Scale Program as Validation Test (VT) and a QC procedure during the production.
The main objective of the BST program was to investigate the impacts of the type and the amount of binder and the influence of the w/b ratio on the UCS of mixtures from the various types of soil that would be treated during production mixing.
According to Leoni and Bertero (2012), the field tests should follow a comprehensive but flexible approach, allowing adjustments and modifications to the parameters initially foreseen as the operations proceed and new or more detailed information is acquired. For that purpose, at the LPV111 project, the Field Scale Program or Validation Test (VT) was conceived to achieve the following objectives:

- verify and refine the type and content of binder, preliminarily determined through the BST, to attain the target mechanical characteristics of the treated soil,
- determine the most appropriate DMM operating parameters and equipment configuration,
- and develop QA/QC procedures for the DMM production stages.

In addition to laboratory mix test campaign, field trial installation is an essential step of the process design because the quality of the DSM material, in terms of strength, stiffness, continuity and uniformity mainly depends on the execution process. Moreover, the laboratory test results are influenced by the test procedure, especially by the method of preparation (mixing time/energy, time between mixing and molding, molding procedure) and by the curing of the specimens (temperature, humidity, potential application of surcharge). Hence, in addition to the laboratory mix test program, a field test program should systematically be performed prior to actual production mixing.

During the production stage, over 500 DSM samples were cored and tested for UCS assessment. All the results were tracked, analyzed, and combined with the other available data from the BST and VT programs on a day-by-day basis to fine tune the production parameters and the QA/QC procedures, and to determine whether corrective actions had to be taken.

All data obtained through the QA/QC program at LPV 111 allowed the optimization of both installation time and cement consumption. Generally, the adjustments were the result of observations carried out in the field and through QA/QC testing during the production stages. Nonetheless, all changes, especially if entailing a reduction of the cement dosage, were validated before they were implemented for the production elements, as prescribed by the project requirements. This iteration gave an opportunity for a better design of the BST and VT stages as the project progressed. The most significant consequence of this process was primarily related to the cement consumption. The dosage of the binder was, in fact, reduced without affecting the overall quality of the ground improvement. As a conclusion, the consideration of the BST, VT, and QA/QC programs allowed the optimization of the mixing parameters and equipment configuration to continuously improve economy and effectiveness as the project progressed.

5.3. Laboratory and field characterization of DSM material for QC

In practice, the quality of DSM material is often controlled with the help of UCS tests regardless of the DSM application. Nevertheless, various tests can be performed to determine characteristics of DSM material. Table 8 summarizes several case histories of the Deep Mixing session with regard to the application of the DSM structure and provides some information concerning the QC aspects of the project.

As illustrated in Table 8, the most common testing method for the mechanical characterization of the DSM material is related to the **realization of UCS tests on DSM samples**. Though, differences still exist between the various projects with regard to the type of test specimens. Indeed, UCS tests can be performed on water/binder mixture samples (Benhamou and Mathieu, 2012), on wet grab samples - from the surface (Lambert et al. (2012), Benhamou and Mathieu (2012), Chapman et al. (2012) and in the contributions of Peixoto et al. (2012)) or recovered at several depths (Gaib et al., 2012) - and finally on core samples (Guimond-Barrett et al. (2012a), Lambert et al. (2012), Benhamou and Mathieu (2012), Pinto et al. (2012) and Gaib et al. (2012)). For several authors and according to the experience acquired within the framework of the BBRI 'Soil Mix' project, cores can be considered more representative than wet grab samples. Nevertheless, coring also presents challenges as explained in Denies et al. (2012c) and illustrated by Gaib et al. (2012) with a case history. DSM samples from fresh material and cores should be collected, from test and final panels, in order to assess the strength and the homogeneity of the material, as well as to perform tests at different ages. In Gaib et al. (2012), UCS tests were conducted at 7, 14 and 28 curing days. The seven day tests were used to provide an indication of any suspect columns, the fourteen day tests to allow comparison to the specification values, and the 28 day tests to ensure that the target strength is met, if there was concern regarding a 14 day result.

In Gaib et al. (2012), **density measurements** of the water/cement mixture and review of the automated batch plant records were taken into account to verify the w/c ratio of the injected mixture. Similar measurements are reported in Guimond-Barrett et al. (2012a) who also determined the density of the spoil produced during mixing to control the blending of the water/binder mixture with the soil.

Several authors also refer to tests for the determination of the **modulus of elasticity** (Benhamou and Mathieu, 2012, Peixoto et al., 2012b and Pinto et al., 2012) and to **tensile splitting tests** (Peixoto et al. 2012b).

In parallel to laboratory mechanical characterization, several authors present results of field tests. Lambert et al. (2012) describe **static load tests** (SLT's) performed on two soil-cement columns, characterized by two different w/c ratios (paragraph 4.2). Their bearing capacity as well as the local response in terms of shaft friction and tip resistance have been analysed. **Plate load tests** are mentioned in Chapman et al. (2012). For the case history reported in Pinto et al. (2012) concerning the slope stabilization (paragraph 4.4), the execution control included **CPT tests**, inside and outside the CSM panels, in order to access the panel's resistance, as well as the confinement effect on the soil located between the panels.

Quasthoff (2012) refers to the **column penetration test** which is the most widely spread testing method for lime-cement columns in Sweden. According to EN 14679, column penetration test is carried out using a probe that is pressed down into the centre of the soil-cement column at a speed of about 20 mm/s and with continuous registration of the penetration resistance. As illustrated in Fig. 33, the probe is equipped with two opposite vanes. The method can normally be used on columns with a maximum length of 8 m and with UCS smaller than 300 kPa. The undrained shear strength of the DSM material can be deduced from the column penetration test.

Table 8: QC of DSM material for several case histories of the Deep Mixing session

DSM functions **and QC information**
Peixoto et al. (2012a) *Permanent earth/water retaining and foundation structure*: monitoring and recording of the execution parameters, UCS tests on wet grab samples from test and production panels. Monitoring plan for the excavation: surveying targets, inclinometers and extensometers in the struts
Peixoto et al. (2012b) *Temporary earth/water retaining wall*: monitoring and recording of the execution parameters, UCS, E and T tests on 36 wet grab samples from test panels. Monitoring plan for the excavation: 5 inclinometers, 5 load cells for the anchors and 17 surveying targets
Peixoto et al. (2012c) *Temporary earth/ water retaining wall*: monitoring and recording of the execution parameters, UCS tests on wet grab samples from test and product panels
Peixoto et al. (2012d) *Temporary earth/water retaining wall*: monitoring and recording of the execution parameters, UCS tests on wet grab samples from test and product panels. Monitoring plan for the excavation: 19 survey targets, 3 inclinometers and load cells for temporary foundation elements
Chapman et al. (2012) *Permanent foundation of tank*: UCS tests on wet grab samples and plate load tests
Peixoto et al. (2012e) *Permanent foundation of an industrial building*: monitoring and recording of the execution parameters, UCS tests at 7 days on wet grab samples
Pinto et al. (2012) *Permanent foundation solution*: monitoring and recording of the execution parameters, UCS and E tests on core samples. Monitoring of building during and after construction *Temporary circular shaft*: monitoring and recording of the execution parameters, UCS and E tests on core samples. Monitoring plan for the excavation: inclinometers *Permanent earth retaining wall*: monitoring and recording of the execution parameters, UCS tests on core samples. Monitoring plan for the excavation: inclinometers and topographic marks *Permanent retaining wall and foundation solution*: monitoring and recording of the execution parameters, UCS tests on core samples. Monitoring plan for the excavation: inclinometers and topographic marks *Permanent slope stabilization and foundation*: monitoring and recording of the execution parameters, UCS and E tests on core samples, CPT's inside and outside the panels. Monitoring plan for the wall behavior: inclinometers and extensometers
Lambert et al. (2012) *Permanent reinforcement of railway platforms and existing foundations*: column excavation, SLT's on 2 columns and UCS tests on wet grab and core samples
Guimond-Barrett et al. (2012a) *Permanent reinforcement of railway platforms and foundations*: monitoring and recording of the execution parameters, grout and spoil density measurements, column excavation, UCS and density determination tests on core samples
Benhamou and Mathieu (2012) *Permanent Geomix caissons vs. liquefaction*: monitoring and recording of the execution parameters, UCS tests on water/binder mixture, wet grab and core samples, determination of the E-modulus and visual analysis of the product material after excavation of one cell of the Geomix caissons
Gaib et al. (2012) *Permanent slope stabilization*: monitoring and recording of the execution parameters, UCS tests on wet grab and core samples at 7, 14 and 28 curing days. Monitoring plan of the slope: inclinometers, surveying targets and LIDAR (LIght Detection And Ranging) measurements

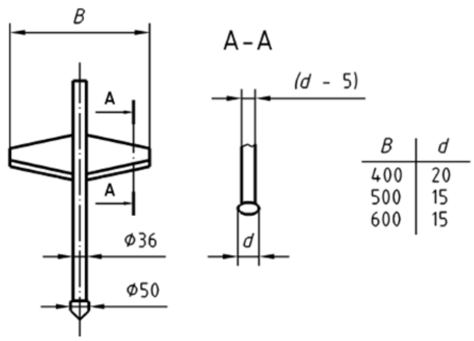

Figure 33: Vanes used in the conventional column penetration test, after EN 14679-2005

Quasthoff (2012) illustrates the use of this method with the help of a case history.

For the control of the **homogeneity and uniformity** of the product DSM material, several authors report the excavation of soil-cement columns or CSM panels. In Benhamou and Mathieu (2012), partial excavation of one cell of the Geomix caisson arrangement was performed after completion of works for the purpose of controlling the visual aspect of the product DSM material (see also paragraph 4.6). Figure 34 illustrates the excavated Geomix caisson. In Guimond-Barrett et al. (2012a), three columns were excavated to verify the column geometry and to examine the homogeneity of the DSM material (see Fig. 35 and paragraph 4.2). Similar work is reported in Lambert et al. (2012) also for soil-cement columns.

Figure 34: Excavated Geomix caisson, after Benhamou and Mathieu (2012)

Figure 35: Excavated soil-cement columns 1 month after construction, after Guimond-Barrett et al. (2012a)

As explained in Holm (2000), uniformity and homogeneity of DSM material can also be controlled computing the coefficient of variation of UCS test results on core samples or comparing field and laboratory UCS test results (calculation of q_{uf}/q_{ul}, where q_{uf} means UCS of core samples and q_{ul} UCS of laboratory mix samples). Nevertheless, in the framework of the BBRI 'Soil Mix' project, a methodology taking into account the amount of unmixed soil inclusions into the mix was developed and illustrated with case studies of DSM material executed in several Belgian soils (Denies et al., 2012b).

5.4. QC by execution monitoring

Beyond the mechanical characterization, the **execution tolerances** and possibly **the continuity and the overlapping of the DSM elements** (columns/panels) must be verified. Locations and verticality of the DSM elements should be controlled during execution. As emphasized by all authors presenting DSM case histories, **the best way to ensure QC during execution is by monitoring, adjusting, recording and reporting the execution parameters**. Current technology allows not only to record execution data but also to visualize the execution parameters during the production process, as illustrated in Fig. 36. For dry and wet mixing, EN 14679 (2005) puts the emphasis on the continuous monitoring (or at least at a depth interval of 0.5m) of the construction parameters as reported in Table 9.

Finally, it is important to note that the recorded execution data must be summarized in a **report for each DSM element for final control of the product**. For example, in Benhamou and Mathieu (2012), verticality data were post-processed to construct the as-built 3D Geomix caisson structure, as illustrated in Fig. 32, allowing the verification of the continuity at different depths.

5.5. QC of the DSM structure by monitoring plan

The implementation of a monitoring plan for an engineering solution allows the reduction of the risk for the neighbouring buildings and structures. If necessary preventive measures can be applied. As reported in Table 8, several authors report temporary or long-term monitoring plan for permanent and temporary DSM structures in the cases of earth/water retaining wall, foundation and slope stabilization applications.

For permanent and temporary earth/water retaining walls, Peixoto et al. (2012a, b and d) report that the control of vertical and horizontal displacements can be performed with the help of a monitoring plan including surveying targets and inclinometers. Extensometers can be placed in pipe struts (Peixoto et al., 2012a) and load cells can be used for monitoring anchors (Peixoto et al., 2012b) and temporary foundation elements (Peixoto, 2012d).

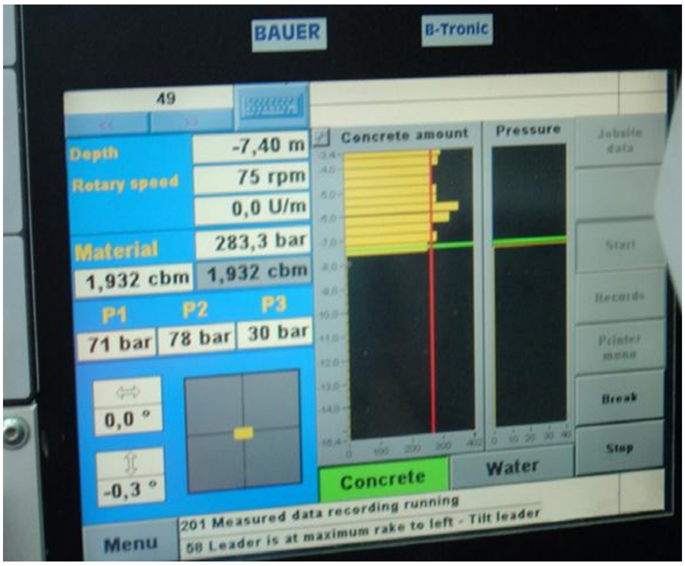

Figure 36: QC monitoring of grout flow rates, injection volume and pressure and penetration rate during execution of CSM walls (photo with courtesy of Malcolm Drilling Company)

Table 9: Construction parameters to be recorded according to EN 14679: 2005

Dry mixing	Wet mixing
Air tank pressure	Slurry pressure; air pressure (if any)
Penetration and retrieval rate	Penetration and retrieval rate
Rotation speed (revs/min. during penetration and retrieval)	Rotation speed (revs/min. during penetration and retrieval)
Quantity of binder per meter of depth during penetration and retrieval	Quantity of slurry per meter of depth during penetration and retrieval

In this way, the recorded values (displacements, deformations and loads) can be compared, on the one hand, with the expected values which can be computed with the help of FEM simulations as reported in Pinto et al. (2012) and, on the other hand, with the alert limits according to the surrounding conditions and the characteristics of the excavation.

For permanent slope stabilization, Pinto et al. (2012) present a monitoring plan including extensometers and inclinometers as represented in Fig. 37. The maximum measured displacements were very similar to the estimated horizontal displacements (5 mm) computed on the basis of the equilibrium limit method and with the help of a 2D FEM analysis (Pinto et al., 2012). The monitoring plan executed in the Fountain slide site (Gaib et al., 2012) includes surveying targets and inclinometers for long term measurements. In addition, aerial LIDAR (LIght Detection And Ranging) measurements have been completed bi-monthly since the completion of the works for the detection of localized slope movement.

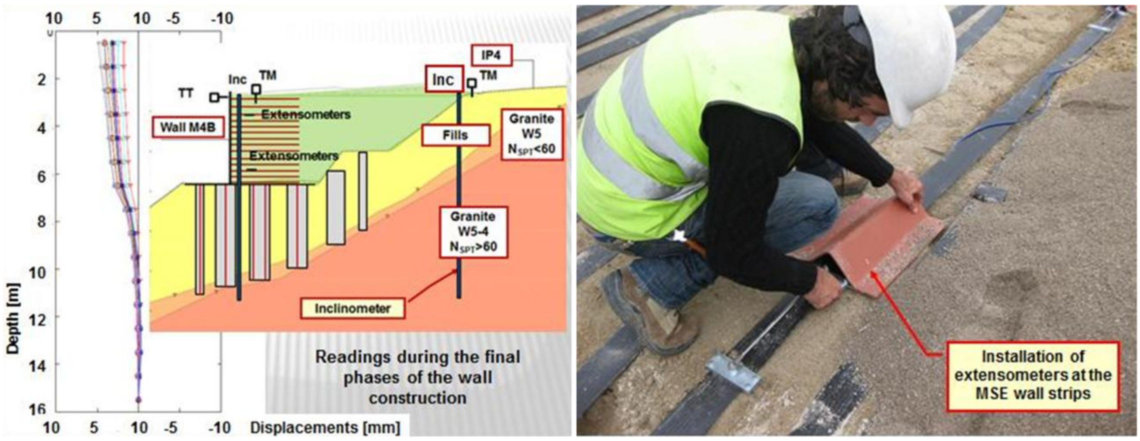

Figure 37: Measured horizontal displacements (on the left) and installation of the extensometers in the retaining wall (on the right), after Pinto et al. (2012)

6. DESIGN RULES

Currently, no universal accepted design approach exists for DSM material. Several methodologies have been presented, though it is still unclear in which way a design value should be calculated for DSM constructions. In this paragraph, an overview of some design methodologies is proposed with regard to the contributions of the Deep Mixing session.

6.1. Methodologies for the determination of the characteristic UCS value

Elements such as piles, diaphragm walls and others comprise only standardized and fully controllable components (Topolnicki and Pandrea, 2012). For these applications the characteristic strength can be defined by the category of concrete. The design procedure for the DSM material is very different since the existing soil is used as an essential component of the final product. Moreover, the characteristic strength depends not only on the soil type, but also on the DSM technique, the amount and type of the binder, etc. In the present proceedings, Denies et al. (2012b) and Topolnicki and Pandrea (2012) discuss the determination of the characteristic strength on the basis of a dataset of UCS values of DSM samples. The paper of Denies et al. (2012b) provides an analysis of several methodologies for the computation of the characteristic UCS value. Topolnicki and Pandrea (2012) present specific design approaches as applied in Japan and Germany.

The first methodology consists in the calculation of the characteristic strength as the X% lower limit on the basis of a distribution function. In both papers, the authors agree that often the wrong assumption is made that the dataset of UCS values is normally distributed (see Fig. 38a). The characteristic UCS value is then erroneously calculated as the X% lower quantile of the normal distribution with parameters corresponding to the dataset. Moreover, this often results into negative and thus useless characteristic UCS values. The correct solution would be to apply the best fitting standard distribution function, for example a lognormal distribution in case the distribution is skewed and/or does not contain subpopulations. The X% lower limit can then be calculated based on this theoretical distribution function, as illustrated in Denies et al. (2012b) for a lognormal distribution (see Fig. 38b). Possibly, a factor β has to be added to the values to obtain an optimal fit with a normal distribution after transformation. Both authors agree that this way of working is probably too complex to apply in practical applications. Denies et al. (2012b) suggest a second methodology to determine the X% lower limit. It is based on the cumulative curve of the original experimental dataset and thus independent of any theoretical distribution function. Note that to apply this method, enough data points have to be available (for the determination of the 5% lower limit, at least 20 samples are necessary) but any other method probably results also in a large uncertainty.

For this first category of approaches (based on the distribution function and based on the cumulative curve of the experimental dataset), Denies et al. (2012b) specify that a value for the X% lower limit has to be defined. In the case of UCS values of DSM material, a more detailed analysis of all the experimental test data is necessary in order to determine if a 5% lower limit, as often stated in Eurocode 7 design, is a representative characteristic strength value.

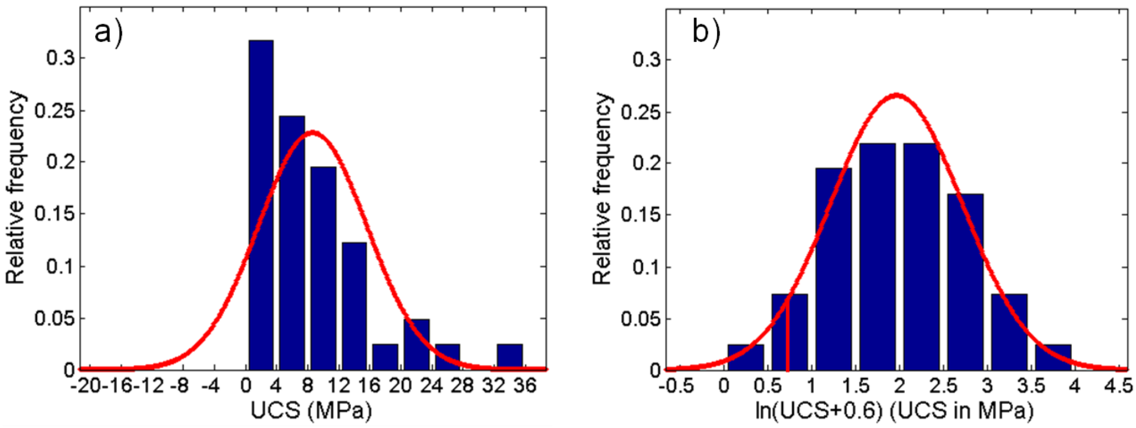

Figure 38: a) Distribution of the UCS values of 41 cores of DSM material from a site in Gent and the corresponding theoretical Gaussian curve. b) Distribution of the logarithm of the UCS values of the same site but increased with β = 0.6 and the corresponding Gaussian curve. The vertical red line indicates the 5% lower limit value, after Denies et al. (2012b)

Denies et al. (2012b) propose a second category of approach to determine the characteristic UCS value which uses the average value of the dataset in combination with a safety factor. This method is described in more detail by Topolnicki and Pandrea (2012) as it has been developed in Japan and Germany for formalized design approach. The characteristic value f_c is then calculated as:

$$f_c = \alpha \overline{q_{uf}} \tag{15}$$

where $\overline{q_{uf}}$ is the mean UCS value from field tests and α a factor representing a certain confidence and safety level ($\alpha < 1$).

In Japan the value of α depends on:

- the coefficient of variation,
- the reliability of the overlap of columns,
- the untreated soil between the columns,
- the difference between field and laboratory data.

In Germany, the characteristic UCS value is defined as the minimum value of three parameters:

$$f_c = \min \begin{bmatrix} f_{m,min} \\ \alpha f_{m,mittel} \\ 12\,\text{MPa} \end{bmatrix} \tag{16}$$

where $f_{m,min}$ is the minimum value found for UCS and $f_{m,mittel}$ the mean UCS value from a series of at least 4 samples.

In order to obtain the design value, both German and Japanese approaches consider global or partial safety factors applied to the characteristic value:

$$f_{c,d} = \frac{f_c}{F_s} \tag{17}$$

where $f_{c,d}$ is the design value and F_s is a safety factor (global or partial).

A factor to consider long term load (for permanent loading) is considered in the German approach. Moreover, if independent and separate design calculations are performed for compressive and shear stresses (i.e. no 3D stress analysis), the maximum allowed compressive stress is 0.7 x $f_{c,d}$ and the maximum allowed shear stress is 0.2 x $f_{c,d}$ (Topolnicki and Pandrea, 2012).

The Japanese approach considers the design value, $f_{c,d}$ as a prediction to find an arrangement pattern for the columns. Hence, it has to be compared with the real results obtained from field. For that purpose, a statistical approach is used based on the number of test specimens and depending on the mixing method (see details in Topolnicki and Pandrea, 2012). In the Japanese approach, a more detailed design calculation including 3D stress analysis has no effect on the safety factors to be applied.

Concerning this third methodology, Denies et al. (2012b) make two important remarks. First, the definition of the mean that is most suitable (arithmetic mean, median, geometric mean, etc.) depends on the type of distribution of the set of UCS values. Second, it is mentioned that problems may arise when:

- the number of samples is limited,
- the population is skewed,
- and when a population is composed of different subpopulations.

Denies et al. (2012b) also note that the DSM samples with soft soil inclusions larger than 1/6 will have a considerable influence on the deduction of the engineering values.

6.2. Reliability-based design (RBD) approaches applied to DSM structures

Al-Naqshabandy and Larsson (2012) propose a partial factor design by using reliability-based design (RBD) approaches. This methodology takes the distribution of all random variables and their correlation into account in a rational way. However, these parameters are often poorly estimated or even unknown. This approach is applied on the geotechnical design of highway embankments, for which the ground properties are improved with lime-cement columns. Since a high degree of uncertainty exists on the ground properties, a deterministic approach, which represents the soil parameters by for example their mean values, is considered to be unsuitable. Instead of this, a partial factor design for safety and reliability assessment is considered. In this way, the authors believe that the uncertainties are treated in a more rational way than when a deterministic design method is used with the application of a global safety factor. This is illustrated by two RBD methods to find the target value of the undrained shear strength of the lime-cement columns. Both methods are applied on a trial embankment with a height of 6 meters (see Fig. 39) and compared with the deterministic results.

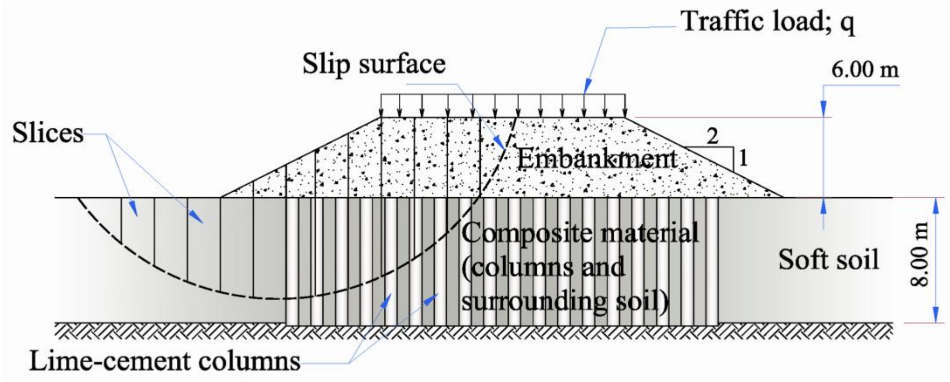

Figure 39: Cross-section of the trial embankment, after Al-Naqshabandy and Larsson (2012)

The first RBD method is known as the first order reliability method (FORM). It takes the uncertainties about the soil parameters into account by including the probability distribution function (PDF) of all random variables and the correlation among them into a performance function. The second RBD method is based on partial factor design and is a more simple form of RBD. Its basic principle is that it replaces the single (or global) factor of safety by a set of partial safety factors of the individual parameters. The partial factors can be evaluated in such a way that they consider different sources of uncertainty associated with the individual parameters.
The study shows that deterministic analysis fails to capture the effect of the total uncertainty on the design of the lime-cement columns. However, this can be avoided relatively easy by the partial factor method, instead of conducting a full probabilistic analysis by FORM.

6.3. Lateral displacements due to installation of soil-cement columns

Because injecting admixtures into the ground under pressure causes deformation of the surrounding subsoil, predicting the lateral displacements and ultimately verifying them are important design considerations. Chai and Carter (2012) present a method for predicting the lateral displacements of the ground induced by the installation of soil-cement columns. It is believed to be the only semi-theoretical method currently available for the analysis of multi-column installation.
In a first step, the prediction method is shortly summarized. It is based on the (cylindrical) cavity expansion theory. The parameters of the method are the diameter of the cavity, R_u, the injection pressure, the volume injected into the soil per unit length of column, the soil shear strength and the Young's modulus of the soil. So far, no theoretical expression for the determination of R_u in terms of all these factors exists. Hence, Chai and Carter (2012) propose empirical equations for the evaluation of R_u. The effect of the construction method is empirically taken into account. The results of the prediction method are finally compared with the results of field tests of two sites in Japan. In both sites, the soil consists of a sandy layer underlain by clays. Below these clays, sandy layers are present again. For these particular sites, it can be concluded that the prediction method generally underestimates the lateral displacement of the clayey layers but overestimates the values of the sandy layers.

7. CONCLUSIONS

The present General Report highlights the significant contributions of the papers of Session 4 of the IS-GI Brussels 2012 dedicated to the Deep Soil Mix (DSM) technique. It is organized with regard to the following aspects: the description of the execution processes and tools, the study of the DSM material, the review of the various applications, the Quality Assurance/Quality Control (QA/QC) requirements and the developments related to the design approaches.

In the DSM process, two types of installation methods are generally considered with regard to the way the binder (based on cement or lime) is injected into the ground: the wet and the dry mixing. Depending on the applications, different improvement patterns can be designed with the help of soil-cement columns, rectangular soil mix panels, continuous barriers or global mass stabilization. In the proceedings of the Deep Mixing session, the following DSM systems have been described in detail:

- the CVR C-mix®, the SMET Tubular Soil Mix TSM®, the Keller Foundations Flapwings® and the Soletanche Bachy Springsol® systems for soil-cement columns,
- the CSM® method for rectangular soil mix panels,
- and the ALLU® mass stabilization for global soil stabilization.

Several parameters have an influence on the produced DSM material: the characteristics of the water/binder mixture, the soil conditions, the mixing conditions (mixing energy and process) and the curing conditions. In the papers of the Deep Mixing session, numerous test results on in situ DSM material have been reported. On the basis of tests on core samples, the density, the UCS, the modulus of elasticity and the tensile strength have been determined, as well as the porosity, the permeability and the ultrasonic pulse velocity. Moreover, the adherence between steel and soil mix has been studied. As illustrated in Fig. 9 and 10, UCS, modulus of elasticity and tensile strength are correlated with the help of equations (1) to (3) and (6) to (8). The results of a methodology taking into account the presence of soft soil inclusions into the mix is then illustrated with case studies. With the help of large scale tests and numerical simulations, the representativeness of the core samples is analyzed with regard to the question of the scale effect and the influence of the unmixed soft soil inclusions.

The mixing technology has to make sure that the soil is mixed sufficiently with the binder to achieve a homogeneous product. For that purpose, the quality control of mixing can be performed with the help of the "*Blade rotation number*" (equation 9) for soil-cement columns or with the help of the "*Mixing quality parameter*" (equation 10) for CSM panels. A procedure is proposed for the estimation of the UCS at 28 curing days with regard to the amount of injected cement, the fine content (FC), the Mixing quality parameter (μ) and if necessary the effects of the *pH*. The effect of curing time on the development of the UCS can be considered with the help of equations (11) to (14).

In the Deep Mixing session, several papers are dedicated to case histories related to various structural and environmental applications of DSM technique: earth/water retaining structure (Table 4), foundation and soil reinforcement (Table 5), land levee (Table 6) and slope stabilization (Table 7), in situ remediation (paragraph 4.5) and barrier against liquefaction (paragraph 4.6). These papers describe the DSM structures with regard to their function, the surrounding soil and the temporary or permanent character of the construction.

Paragraph 5 of the present General Report describes the basics and the recent developments with regard to the Quality Assurance/Quality Control activities related to the DSM technique. The DSM process design can be described by the following steps: a laboratory mix test campaign, a field trial installation, the determination of the final process design (including the definition of the final mix design and construction control values) and the production with QC by monitoring. This DSM process design is illustrated with a case history. In addition, BBRI info sheets (Denies et al. 2012a) have been developed in the continuity of the European standard EN 14679 – 2005 for deep mixing. They provide for the owner/contractor/engineer practical criteria in terms of the execution sequence and tolerances and give some requirements with regard to the quality of the DSM material.

In practice, the DSM material quality is often controlled in laboratory with the help of UCS tests performed on water/binder mixture, wet grab and core samples at different ages. The determination of the density, the coefficient of permeability, the modulus of elasticity and the tensile strength can be required. In the present Deep Mixing session, results of field tests (SLT's, plate load tests, CPT's and column penetration tests) are also presented. For the control of the homogeneity and uniformity of the product DSM material, several authors refer to the excavation of DSM elements. The execution tolerances and possibly the continuity and the overlapping of the DSM elements must be verified. According to all authors of case histories, locations and verticality of the DSM elements should be controlled during execution by monitoring, adjusting, recording and reporting the execution parameters. In addition, the implementation of a monitoring plan for the post-control of the DSM structure can be required.

Finally, paragraph 6 gives an overview of some design methodologies for the determination of the characteristic UCS value for the DSM material. These methodologies can be divided into two categories. The first one uses the average value of the population combined with a safety factor, while the second category defines the characteristic value as a lower limit (e.g. 5% quantile). Moreover, two methodologies are presented to calculate this lower limit. The first methodology consists in the computation of the characteristic strength as the X% lower limit on the basis of a distribution function. The second

methodology is based on the cumulative curve of the original experimental dataset. For these two approaches the X% lower limit has to be defined for DSM material in particular with regard to the amount of soft soil inclusions in the mix.
The first category is discussed with regard to the Japanese and German formalized design approaches. In parallel, a partial factor design for safety and reliability assessment is considered on the basis of the reliability-based design (RBD) approaches. Finally, a semi-theoretical method for predicting the lateral displacements of the ground induced by the installation of soil-cement columns is presented.

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