General Report of TC 211
Ground Improvement

Rapport général du TC 211
Amélioration des sols

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ABSTRACT: The present General Report highlights the significant contributions of the papers of the Session of the XVIII ICSMGE dedicated to Ground Improvement. All papers that have been reviewed are referred (in bold) in the General Report in order to provide a balanced overview of the entire Technical Session.
This General Report discusses the latest developments and current researches in the field of Ground Improvement (GI) works. The various GI techniques are classified considering the recent classification proposed by Chu et al. (2009). The papers are then tackled according to the described GI technique and with regard to the topics that are assessed: execution process, mechanical characterization of the treated material (in laboratory or in situ), case history, Quality Assurance/Quality Control (QA/QC) activities and design aspects. Conceptual works and numerical modeling are supported by laboratory and field investigations - with in situ monitoring and large scale tests. Finally, other references on the topics discussed are also given in the report.

RESUME : Le présent rapport général met en évidence les contributions significatives des articles de la session « amélioration des sols » de la 18ème CIMSG. Tous les articles revus ont été référencés (en gras) dans le rapport général de manière à fournir une vue d'ensemble équilibrée du contenu de cette session.
Ce rapport discute des derniers développements et des recherches actuelles dans le domaine des travaux d'amélioration des sols. Les différentes techniques sont classées selon la récente classification proposée par Chu et al. (2009). Les articles sont ensuite abordés en tenant compte de la technique d'exécution décrite et du sujet choisi par les auteurs : procédé d'exécution, caractérisation mécanique du matériau traité (en laboratoire ou in situ), cas pratique, activités de contrôle et d'assurance du point de vue de la qualité et aspects liés au dimensionnement. Les approches de conception et la modélisation numérique sont supportées par des recherches en laboratoire et par l'expérience de chantier – apportée par le monitoring in situ et par les essais en grandeur réelle. Finalement, d'autres références concernant le domaine de l'amélioration des sols sont aussi indiquées.

KEYWORDS: ground improvement/reinforcement, deep mixing, drainage, geosynthetics, grouting, inclusions, vacuum consolidation

1 INTRODUCTION

Ground improvement (GI) is one of the major topics in geotechnical engineering. With regard to the world population growth and in response to the expansion needs of our society, it has become a fast growing discipline in civil engineering as an alternative allowing construction on soft/weak/compressible soils. Various specialized ground improvement conferences have been frequently held in the past and recent years such as the International Symposium on Ground Improvement organized by the Technical Committee 211 of the ISSMGE and recently held in Brussels (Denies and Huybrechts, 2012) especially with more than 140 papers and 7 General Reports focusing on GI works. A number of books covering various topics on ground improvement have been also published in the past. Most of them are referred in Chu et al. (2009). During the last decades the importance of the ground improvement market has enormously increased. New methods, tools and procedures have been developed and applied in practice. In order to support this evolution in a scientific way, research programs have been and are being carried out worldwide, leading to more and better insights and delivering the basis for the establishment of design methods, quality control procedures and standards. As a result, many technical papers on GI works were published in journals and conference proceedings. It is not possible to mention all. Separate lists are given on the TC211 website (www.bbri.be/go/tc211). Major GI techniques have been documented by the Working Groups of TC211 and are currently available on this website.

TC211 adopts a classification system as shown in Table 1 in Chu et al. (2009) with the following categories (and methods):

- A. GI without admixtures in non-cohesive soils or fill materials (dynamic compaction, vibrocompaction,…)
- B. GI without admixtures in cohesive soils (Replacement, preloading, vertical drains, vacuum consolidation,…)
- C. GI with admixtures or inclusions (Vibro replacement, stone columns, sand compaction piles, rigid inclusions,…)
- D. GI with grouting type admixtures (Particulate and chemical grouting, Deep mixing, jet grouting,…)
- E. Earth reinforcement (geosynthetics or MSE, ground anchors, soil nails,…)

This classification is based on the broad trend of behaviors of the ground to be improved and whether admixture is used or not. In the following sections, the papers of the Session of the XVIII ICSMGE dedicated to GI works will be reviewed according to this classification and with regard to the topics that are assessed: execution process, mechanical characterization of the treated material, case history, QA/QC activities and design aspects. It can already be noted that there is no paper considering GI without admixtures in non-cohesive soils (category A) in the present Technical Session.

2 GI WITHOUT ADMIXTURES IN COHESIVE SOILS

In the present Technical Session, six papers can be put in the category B: GI without admixtures in cohesive soils. They are mainly related to the subject of consolidation acceleration by vertical drains combined with surcharge or Vacuum. The interest seems to be oriented to the approach of "smear". **Parsa-Pajouh et al. (2013)** address this delicate topic so difficult to model due to the lack of field parameters. According to the authors, the smear zone varies between 1.6 and 7 times the drain radius or 1 to 6 times the mandrel equivalent diameter. Numerical models are used within the framework of case studies. Parameters studies confirm their validity. As a result of their researches, it is recommended to assess the smear zone on the basis of trial construction with the help of back calculation process.

Chai and Carter (2013) present a theoretical approach of Prefabricated Vertical Drains (PVD) and consolidation combining vacuum pressure and surcharge loading. Using Hansbo's (1981) solution, consolidation parameters of the smear zone and the undisturbed zone were derived using a simple equation. Adopting an average well resistance and with some approximation, the dimensionless parameter μ quantifying the effects of PVD spacing, smear zone and well resistance can be expressed. The study was performed in uniaxial consolidation condition, which is not in agreement with the real isotropic character of deformation under Vacuum. Moreover, the classical assumption of uniform smear zone cannot be measured. However the pore pressure measurements of the tested samples are in extreme close concordance with the prediction confirming the validity of the approach and the selected parameters.

Indraratna et al. (2013) treat similar subject in conjunction with a real construction site in the Port of Brisbane where the consolidation of thick Holocene clays was performed with PVD's under surcharge and/or Vacuum loading. Variable drain spacing was selected and analytical solutions were proposed. For the excess pore pressure dissipation, the same equation as in Chai and Carter (2013) was adopted. The results demonstrate that Vacuum combined with preloading would speed up consolidation compared to preloading alone. Moreover, Vacuum results in isotropic consolidation increasing the stability of the surcharge fill (decreasing lateral displacements).

In a similar way, **Lee et al. (2013)** have also studied the effect of the smear zone for a consolidation case history in Busan (South Korea). Modification of Hansbo's analysis is proposed to study the degree of consolidation considering the properties of the soil within the smear zone.

As another case history, **Islam and Yasin (2013)** present an application of PVD's coupled with preloading used for the construction of a large container yard in Bangladesh. The soil profile consists of 4 to 6 m thick silty clay, 8 to 10 m of sand and silt and 16 m of clayey silt. On the basis of design requirements, GI of the upper soft clay layer was considered essential. Five alternatives were assessed and compared. A solution combining PVD and preloading was adopted for this site. The settlement under preloading was monitored during the consolidation phase. Pre and post consolidation SPT tests are presented to illustrate the efficiency of the technique. It is believed that dynamic compaction although economical would not have been technically feasible due to the clayey nature of the upper fill. However, dynamic replacement in the upper 4 m with densification of the lower silty sand might have been technically and financially optimal.

For their part, **Jebali et al. (2013)** have assessed the theory of Carillo using three different oedometer tests carried on Tunis soft soil. Oedometer tests were conducted, conventionally (NF P94-90-1) for the first test, with a vertical drain allowing only radial drainage for the second one and finally with a drain allowing vertical and radial drainage for the last one. Defining C_r and C_v as the radial and vertical coefficients of consolidation and K_r and K_v as the coefficients of radial and vertical permeability, they observed that the often-made assumption of the equality between the ratio's C_r/C_v and K_r/K_v is only valid at high levels of stress conditions. Moreover, on the basis of experimental results, the authors demonstrated that the global degree of consolidation computed with respect of the Carillo's theory can lead to underestimated consolidation times.

The paper of **Weihrauch et al. (2013)** describes a combination of GI methods for the improvement of roads in the HafenCity area in Hamburg. Indeed, in the Hamburg Harbour area, many roads are lifted with almost 3 m to ensure safety in case of flooding. Special measures are necessary when the subsoil contains compressible layers. At the Hongkongstrasse, three different construction methods have been applied, namely:

- installation of PVD and preloading with sand (settlements of more than 30 cm have been measured);
- filling with lightweight aggregate: expanded clay (almost no settlement was observed);
- pile supported embankment including geogrid-reinforced sand layer (measurements are discussed in another paper).

The different aspects of each method are described. The conclusion is that when comparing different methods, not only the absolute costs must be ascertained, but also the project specific reconstruction, protection and follow-on measures, as well as the time and flexibility for individual measures, and their technical feasibility under local conditions.

3 GI WITH ADMIXTURES OR INCLUSIONS

3.1 *Rigid inclusions*

Moving towards category C, GI with admixtures or inclusions, the paper presented by **Kirstein and Wittorf (2013)** is an interesting transition between categories B and C. Indeed, the authors describe the improvement of soft fat clay using rigid inclusions combined with vertical drains, preloading and the use of geotextile. The aim of the project was the construction of a bridge for a new road in Germany including 1.5 to 7 m high embankments. Vertical drains were first used to accelerate the consolidation under the embankments (preloading condition). Even using 600 kN/m woven geotextiles, vertical settlement of around 1.5 m and horizontal displacement up to 27 cm were measured throughout one year of monitoring. Because the bridge could not tolerate residual settlements, Controlled Modulus Columns (CMC) were designed and executed. The design of the transition interface between the bridge and the embankment, referred as the Load Transfer Platform (LTP), was confirmed by the monitoring.

Cirión et al. (2013) set the constructive procedures and bases of design of rigid inclusions including the LTP. The ASIRI guidelines (IREX, 2012) were not yet published at the time of preparation of this paper. The paper highlights the difference with pile foundation. In rigid inclusion solutions, there is no mechanical link between the pile and the structure. A LTP is usually placed between the inclusions and the structure. This distribution layer spreads the acting loads from the structure towards the underlying soil-inclusions setup. As indicated by the authors, isolated or continuous footings can possibly be used to directly transmit the loads to the soil-inclusions setup. This GI technique can also be applied for embankments and landfills.

The following paper constitutes a good transition with the next topic concerning stone columns. According to **Carvajal et al. (2013)**, dealing with the design of Column Supported Embankments (CSE), a clear distinction has to be made between rigid inclusions (e.g. concrete type columns) characterized by a brittle behavior in its Ultimate Limit State

(ULS) and stone columns (made of gravel and sand) which demonstrate a ductile behavior in its Serviceability Limit State (SLS) due to its compressibility and drainage characteristics (influence of the consolidation process on the design). Due to the brittle behavior of concrete type columns, larger safety factors have to be introduced, certainly for very slender elements. The General Reporters fully agree that similar approaches cannot be applied for very slender concrete type columns and for stone columns. However it has to be remarked that it is not common to consider stone columns as drainage elements.

3.2 *Stone columns*

In the present Technical Session, **Vlavianos et al. (2013)** propose technical solutions for the design of a road project in the Region of Western Greece. The geology of the site consists of soft silty clays and silty sands with high liquefaction susceptibility. The high ground water table and the seismicity of the area result in a design solution including GI. The installation of stone columns followed by preloading was selected. For the design of the bridge embankments and the pile foundations for bridge piers, a comparative parametric study was performed with or without stone columns. As discussed by the authors, the main aim of the preloading was the increase of the undrained shear strength of the superficial fine-grained soil layer. With the installation of the stone columns, the following requirements were met:

- increase of the general stability of the embankments;
- increase of the bearing capacity;
- reduction of the internal forces in the classical pile foundations;
- acceleration of the consolidation process;
- mitigation of the liquefaction susceptibility.

Although "stone columns" is nowadays a well-known GI method, installation effects arising during the execution still remains poorly understood. In order to investigate this question, **Klimis and Sarigiannis (2013)** describe the numerical analysis of the installation of stone columns with a diameter of 0.8 m and a depth of 23 m by means of the FLAC 3D Finite Difference code. The excavation stage has been modeled in one unique step and the realization of the stone column as follows:

- a) vibration and compaction, modeled by the application of an equivalent radial pressure against the internal wall of the cylindrical excavation;
- b) filling with a linear elastic geomaterial.

This numerical sequence was necessary to correctly determine the area in the surrounding soil influenced by the installation of the stone column and hence to assess with more accuracy the effective diameter of this latter.

Poon and Chan (2013) present another methodology to design stone columns. In this analysis, stone columns are replaced by equivalent strips, as illustrated in Fig. 1. The equivalent friction angle of the strips is dependent of the stress concentration ratio which is defined as the ratio of the average applied vertical stress within stone column to the average vertical stress of the surrounding soil at the same level. A method is proposed to compute this ratio by means of an axisymmetric Finite Element Model (FEM) containing one column and the surrounding soil. Numerical results obtained with this methodology (2D FEM with strips) have been compared with the results of a 3D FEM and with the results of a conventional 2D FEM analysis in which the entire soil is represented by a single block with equivalent properties. The authors conclude that the strip model is preferable to the block model for the assessment of the horizontal displacements. Further research is still necessary to investigate the question of the equivalent strength of the interface in the 2D strip method.

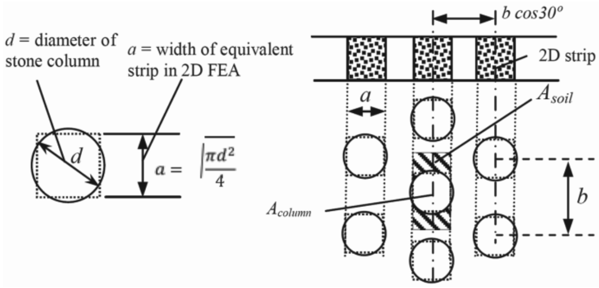

Figure 1. 2D stone column strips, from Poon and Chan (2013)

3.3 *Geotextile confined columns*

Rigid inclusions are a common GI technique for foundations of embankments in soft soils. Nevertheless, when the soft soil does not provide enough lateral support, the columns can be encased with a geotextile. The following papers mainly focus on the geotextile confined columns, also defined as geoencased granular columns (GEC's).

Castro et al. (2013) describe and compare analytical and numerical analyses considering the behavior and the performances of geotextile confined columns (GEC's). Parametric studies of the settlement reduction and stress concentration show the efficiency of GEC's for GI purposes. This efficiency is mainly related to the contrast of stiffness between the encasement and the soil. As another conclusion, it is found that the settlement reduction is nearly the same for different replacement ratios but decreases with the applied load. Finally, columns with smaller diameter are better confined.

If GEC's are often used to reduce settlements induced by the construction of large embankments on soft soils, up to now no rational displacement based design approach has been introduced. For the purpose of investigating this question, **Galli and di Prisco (2013)** first review the most common design standards and then focus on the interaction between the embankment and the geoencased columns. The main contribution of the paper resides in the consideration of the deformable base of the embankment. Indeed, real embankments are characterized by a deformable base, as illustrated in Fig. 2. As a consequence, different values of settlement are expected for the top of the column (u_c) and for the soil (u_s) at the base of the embankment. As explained by the authors, vertical stresses are redistributed at the base of the embankment between the internal zone of the cell (above the column characterized by an average stress σ_i) and the external one (a circular crown above the soil, characterized by an average stress σ_e) due to the arch effect. Shear stresses are then activated at the GEC-soil interface, and differential settlements are expected even at the top of the embankment.

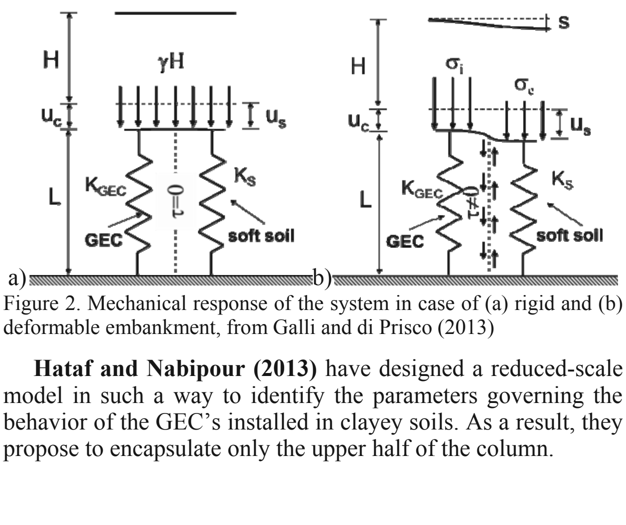

Figure 2. Mechanical response of the system in case of (a) rigid and (b) deformable embankment, from Galli and di Prisco (2013)

Hataf and Nabipour (2013) have designed a reduced-scale model in such a way to identify the parameters governing the behavior of the GEC's installed in clayey soils. As a result, they propose to encapsulate only the upper half of the column.

3.4 *Geosynthetic reinforced column or pile supported embankment – the use of geogrids*

Another way to use geosynthetic material for GI application is the design of geogrids for the support of embankment, land levees, yards and structure foundations (slabs and superficial isolated or continuous footings).

Investigating the use of geosynthetics for reinforcement under ground mass collapse, **Ponomaryov and Zolotozubov (2013)** compare the method outlined in British Standard BS 8006 and several design approaches with numerical calculations. On the basis of experimental elongation results, they introduce the ratio of actual tensile force to deformation. Computational assumptions are proposed for the description of the mechanisms of stress-strain development in the reinforced ground mass. The authors finally present a comparison between experimental measurements and the results of seven different methods used for the calculation of the tensile force in the geosynthetic, its deflection and the surface settlement.

Mihova and Kolev (2013) analyze the benefit of a geosynthetic reinforced pad of crushed stone used for the foundation of a hall in Sofia over soft saturated soil. Field tests were performed to estimate the E-moduli before and after improvement. The authors also conducted Finite Element analysis to model the consolidation process and to confirm the design stability under static and seismic conditions.

Dimitrievski et al. (2013) present a history case of soil reinforcement with geosynthetics for the construction of a six-storey structure in Ohrid (Republic of Macedonia). Multi layers geogrids were designed and the effects of the geostatic, hydrostatic and dynamic loading conditions were studied with the help of FEM calculations. The validity of the analysis was demonstrated with the help of in situ measurements obtained for a close similar structure.

3.5 *Sand compaction piles (SCP's)*

In the sand compaction pile (SCP) method, sand is fed into the ground through a casing pipe and is compacted by vibration, dynamic or static compaction to form columns. In practice, SCP's are mainly used to prevent liquefaction and reduce settlement with similar success in sandy and clayey soils. With the help of laboratory and field tests, **Burlacu et al. (2013)** investigate the potential of columns made of loess-sand-bentonite mixture for the reinforcement of collapsible loess deposits in Romania. Indeed, as explained in the paper of **Alupoae et al. (2013)**, these collapsible soils require GI works. They are characterized by high water sensitivity: when its water content increases, important deformations in the soil can be observed. In such a way to illustrate this phenomenon, the authors present a case study of differential settlement of buildings founded on loess sensitive to wetting. In spite of the good realization and control of the foundation, important differential settlements were measured thereafter as a result of the defective rainwater recovery system.

3.6 *Microbial methods*

The use of microbially induced carbonate precipitation (MICP) to cement cohesionless soils has recently received substantial attention from geotechnical researchers. The most common MICP mechanism is hydrolysis of urea. MICP via ureolytic hydrolysis relies on microbes to generate urease enzyme, which then serves as a catalyst for the calcium carbonate ($CaCO_3$) precipitation reaction. If it is to date well known that the mechanical properties of the treated soils are directly correlated to the amount of ($CaCO_3$) precipitation, a gray area still remains concerning the influence of the original nature of the granular material on the resulting properties of the treated soil. Within the framework of a laboratory campaign, **Tsukamoto et al. (2013)** investigate the influence of the relative density of sand samples on the MICP. As a result of their study, the MICP tends to increase as the relative density of the soil decreases. Nevertheless, considering the results of triaxial tests, maximum principal stress differences were obtained for the samples with the highest relative density. In light of these results, this technique seems to be very promising for the future but due to the bioplugging (permeability reduction) of the granular material and to the generation of toxic product (ammonium salt); soil stabilization using ureolytic MICP remains currently unusual. According to **Hamdan et al. (2013)**, the use of plant derived urease to induce the carbonate cementation could be the solution to avoid these drawbacks.

4 GI WITH GROUTING TYPE ADMIXTURES

4.1 *Deep Mixing Method (DMM) and soil stabilization*

The deep mixing method (DMM) is nowadays a worldwide accepted GI technology. In this method, 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. Numerous reviews and recent progresses of the DMM are referred in Denies and Van Lysebetten (2012). In the recent years, the DMM is undergoing rapid development, particularly with regard to its range of applicability, cost effectiveness and environmental advantages, as illustrated by the papers of this paragraph.

In the deep mixing projects, the design can be based on laboratory mixing tests. Soil-cement samples are then prepared and tested to study the mechanical properties of the stabilized soil. But, up to now, many laboratories prepared these samples without standardized procedure. Actually, molding techniques have a great influence on the mechanical characteristics of the stabilized material. According to **Grisolia et al. (2013)**, this influence is strictly correlated to the workability of the soil-cement mixture and this latter can be quantified with the measurement of the torque required to turn an impeller in the mixture. Five molding techniques have been studied and the authors propose the abacus illustrated in Fig. 3 to define the range of applicability of these techniques in function of this torque.

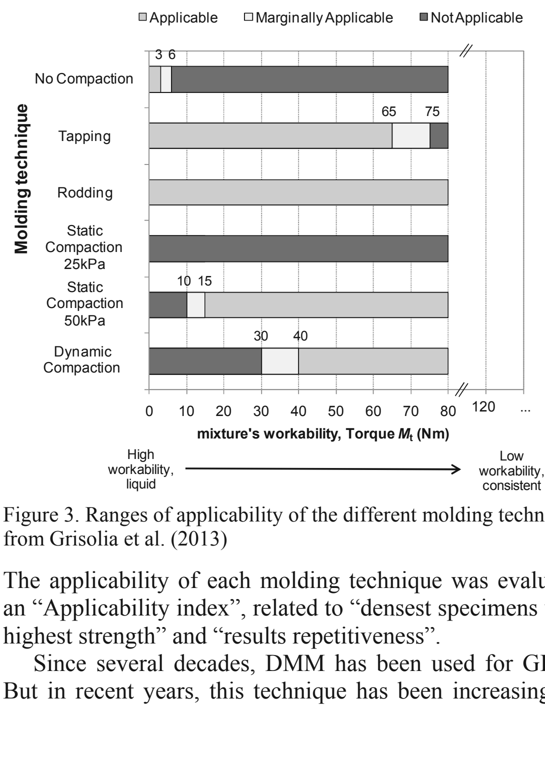

Figure 3. Ranges of applicability of the different molding techniques, from Grisolia et al. (2013)

The applicability of each molding technique was evaluated by an "Applicability index", related to "densest specimens with the highest strength" and "results repetitiveness".

Since several decades, DMM has been used for GI works. But in recent years, this technique has been increasingly used for structural applications. Standardized guidelines for the design of this kind of applications are not currently available. If the previous work allows the construction of standardized and international test procedures for laboratory mix samples, the Quality Control (QC) of the execution process is generally based on the results of Unconfined Compressive Strength (UCS) tests performed on cored material. As part of the semi-probabilistic design approach presented in Eurocode 7, it is thus essential to define the UCS characteristic value that can be taken into account in the design. **Denies et al. (2013)** discuss the definition of this value. In the first category of approaches, the characteristic strength is defined as an X% lower limit value computed either on the basis of a statistical distribution function or based on the cumulative frequency curve of the original experimental dataset of UCS values obtained from tests on cored samples. A second approach to determine the UCS characteristic value is the use of the average value of the dataset in combination with a safety factor. For the first category of approaches, a value for the X% has to be defined. Actually, one major issue is the representativeness of the core samples with regard to the in situ executed material. For the purpose of investigating this question, the authors present the results of a study on the influence of soil inclusions and then they discuss the topic of the scale effect with regard to large scale UCS tests.

The following papers concern the investigation of the mechanical properties of the soil mix material under the field of laboratory or in situ experiments and with the help of numerical modeling.

In such a way to investigate the properties of the soil mix material, **Szymkiewicz et al. (2013)** have carried out a parametric study on lab soil-cement mixtures. The influences of the particle size, the clay content and the water content on the strength of the material were considered. They propose an abacus relating the UCS of the specimens to the cement content. Six zones are identified in the abacus depending on the nature of the soil. In addition, the authors also propose a formula valid for granular soils for the estimation of the UCS at 28 curing days. This formula takes into account the water, the cement and the fine contents.

In a similar way, **Correia et al. (2013)** have performed laboratory tests to study the improvement of soft clayey silt with high organic content by mixing it with a binder made up of 75% Portland cement (PC) and 25% blast furnace slag. They first give a formula for the assessment of the UCS at 28 days in function of the binder content and the liquidity index (LI) of the soil. A normalized UCS is then introduced as follows: $UCS_{LI} = UCS \times LI$. In a second step, the applicability of the normalized UCS approach is analyzed for seven other cement-stabilized soft soils with successful result.

If the water/cement (w/c) ratio is often used in attempt to understand soil-mix properties, it can be found limited since in practice execution is mostly performed in soils in the presence of water (unsaturated or saturated conditions). A well-adapted governing parameter could be then the porosity/cement index defined as the ratio of porosity to the volumetric cement content (n/C_{iv}). **Rios et al. (2013)** highlight the influence of this index on the mechanical properties of cemented Porto silty sand. Unique trend was obtained between the UCS and an adjusted porosity/cement ratio ($n/C_{iv}^{0.21}$), proposed by the authors. Similar observation was also made with indirect tensile strength. Triaxial tests resulted in two peak strength envelopes for each predetermined $(n/C_{iv})^{0.21}$ and finally, oedometer tests establish this ratio as the governing parameter of the behavior of the soil-cement specimen in one-dimensional compression in lieu of the cement content or the initial void ratio.

A major advance in DMM could be found in the contribution of **Yi et al. (2013)** with the investigation of the carbonation of reactive magnesia (MgO) for soil stabilization. Nowadays, Portland cement (PC) is the most common binder used in the deep mixing applications. However, there are significant environmental impacts associated with its production in terms of high energy consumption and CO_2 emissions. In their laboratory study, reactive MgO was used as a binder and the MgO-soil samples were carbonated by CO_2 to improve the mechanical properties of the soil and reduce the CO_2 emission. As an evident result, the UCS values of the uncarbonated MgO-stabilised soils were much lower than those of the PC-stabilised soils; both mixes took ~28 days to finish most of their strength development. Nevertheless, the carbonation process significantly increased the UCS of MgO-stabilised soils in a very short time, this latter fast reaching the UCS value of the 28-day PC-stabilised soils, indicating that it could be used to support a structure just after the completion of the carbonation procedure.

Another type of binder largely used for soil stabilization is lime. **Mesri and Moridzadeh (2013)** discuss the results of a laboratory study focusing on the improvement of the Brenna clay (high plastic lacustrine clay of North Dakota) by adding lime. Lime contents varying between 3 and 10 % of the dry weight of the clay have been considered. The authors observed a decrease of the measured pH with time and an increase of the Liquid Limit and the Plasticity Index with time when 5 % of lime was added. Adding 3 to 8 % of lime, the residual friction angle (in drained conditions) increases between 3 to 6 %. Unfortunately the laboratory test results were not compared with full scale test results.

Extensive laboratory tests have been performed by **Szendefy (2013)** for the purpose of determining the effect of lime stabilization on 21 Hungarian clayey soils. In addition, some in situ stabilized soils have also been analyzed. According to his study, the improvement of the clayey soil with the lime is mainly related to the coagulation of the clay particles related to the cation exchange. Indeed, during the stabilization with lime, Ca^{2+} ions attach to the surface of clay particles. As a result of this high charging, the clay particles coagulate resulting in a material characterized by an increased internal friction angle. The pozzolanic reaction would play then a secondary role in the stabilization.

Soil stabilization can also be performed with fiber reinforcement, such as discussed in **Madhusudhan and Baudet (2013)**. In their study, laboratory tests have been performed to determine the influence of adding polypropylene fibers on the shear strength characteristics of completely decomposed granite (CDG). In Hong Kong, CDG is regularly used for landscaping and as green cover of existing shotcrete slopes. The test results clearly indicate an important increase of the UCS when adding 0.5% of fibers and compacting the CDG at the water content close to the optimum Proctor value. In triaxial drained tests, the addition of fibers seems to increase the shear strength of the CDG and its stiffness. Dilation is also reduced.

In Singapore, laboratory tests have been performed by **Xiao et al. (2013)** in order to determine the characteristics of the Singapore upper marine clay when mixed with 20 to 50% Portland cement (PC) and up to 0.32% fibers of different types. As a result of their study, strength and ductility of cement-treated clay were improved by fiber reinforcement. There is an optimum fiber content with regard to performance and workability of the material. Polyvinyl alcohol (PVA) fibers are generally more efficient than polypropylene (PP) fibers except for low cement and water contents. The length of the fibers has a significant effect on the ductility of the cement-treated clay for both fiber types. Concerning the strength, the influence of the fiber length is more significant for PVA reinforcement than for PP reinforcement.

Cuira et al. (2013) present the results of numerical models simulating an axial Static Load Test (SLT) on a soil-cement column. Numerical and experimental results are compared with the help of three Finite Element models and one simplified semi-analytical model. Numerical results are in agreement with the experimental observations all along the SLT but especially regarding to the fracture pattern: structural failure localized in the upper part of the column. This numerical study highlights the nonlinear behavior of the soil-mix material. In comparison with classical "rigid" piles, the contrast of strength (and stiffness) between the column and the soil is lower and has a huge influence on the global behavior.

Originally, DMM was developed for GI applications in soft clays and organic soils. But more recently, it was also dedicated to various structural and environmental applications such as illustrated by the following case histories.

Recently, the DMM has been chosen for several Hungarian railway projects involving soft soils, such as the restoration of the "Sárrét" railway line crossing an area where the subsoil consists of soft chalky silt. For the foundation of a 4m high embankment, two DMM were taken into account: the mass stabilization and the soil-cement columns. **Koch and Szepeshási (2013)** firstly describe results of laboratory tests on chalky silt samples mixed with cement for different w/c contents. Both DMM are then assessed using 3D-FEM considering the site requirements in term of stability and settlement.

In a similar way, DMM have been widely used in Japan for the improvement of soft clays and organic soils. **Matsui et al. (2013)** introduce the concepts of an hybrid application of soil-cement columns combined with soil mix walls (SMW) designed for the foundation of an embankment. The concept is illustrated in Fig. 4. The authors propose a conceptual method allowing the control of ground deformation and ensuring an optimization of the volume of treated soil. The method is supported by 2D-FEM and in situ monitoring is performed for the validation of the concept.

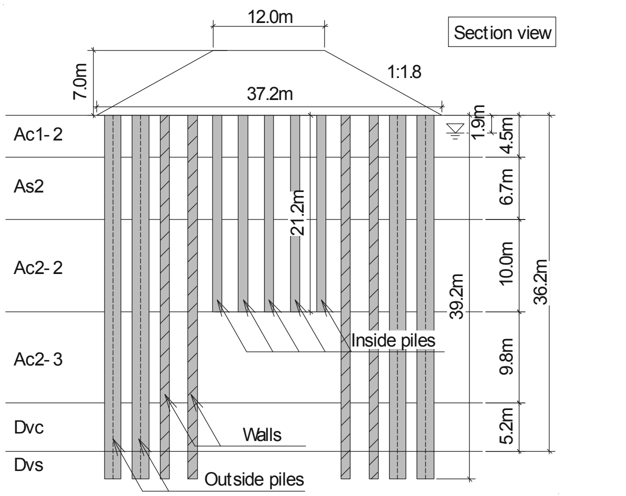

Figure 4. GI with soil-cement columns and SMW, from Matsui et al. (2013)

In Lund (southern Sweden) a new generation synchrotron radiation facility, called MAX IV, is under construction. According to **Lindh and Rydén (2013)**, it should be 100 times more efficient than any existing comparable synchrotron radiation facility in the world. For this kind of facility, the vibration requirements are very stringent. Various alternatives were discussed and simulated during the conception. The optimum solution was achieved with a four meter thick layer of stabilized soil below the concrete foundation. A combination of quicklime and ground granulated blast furnace slag (GGBFS) was found to be in agreement with both design and construction requirements.

Jeanty et al. (2013) describe the use of the CSM and the Trenchmix methods for the realization of SMW. Both techniques are explained in details and different applications are presented, namely: settlement reduction, improvement of slope stability, reduction of active pressure on retaining walls and decrease of liquefaction susceptibility. The two last topics are then illustrated with case histories.

Other case history tackles the topic of liquefaction susceptibility restrained with the DMM. **Yamashita et al. (2013)** deal with the measurements performed underneath a piled raft completed with SMW to reduce the risks of liquefaction. It concerns a 12-storey office building. The load distribution between piles, SMW and the surrounding soil has been monitored during a period of three years. After the end of the construction, settlements of 20 mm have been recorded, as illustrated in Fig. 5. As another result, 70 % of the load was taken by the piles, 14 % by the SMW and 15% by the soil, as shown in Fig. 6. The measurements also learned that the Tohoku earthquake of March 2011 had almost no influence on the settlements and on the load distribution.

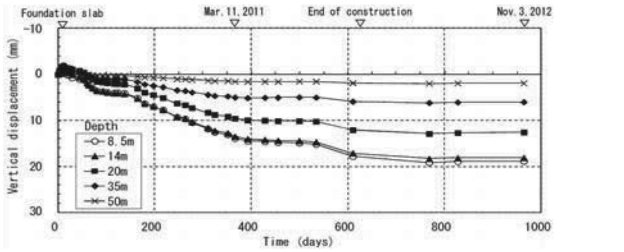

Figure 5. Measured vertical ground displacements below raft, from Yamashita et al. (2013)

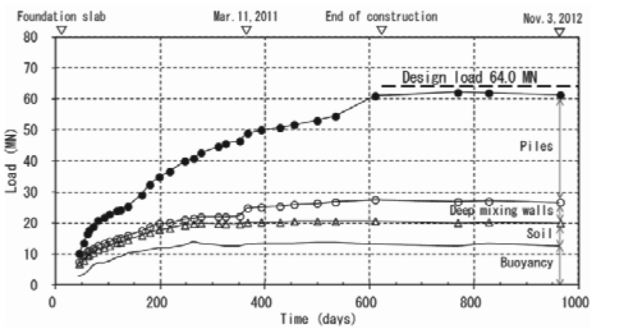

Figure 6. Time-dependent load sharing between raft and piles, from Yamashita et al. (2013)

If the foundation of embankments and buildings are become both common applications of the DMM, underpinning with soil mix material constitutes an interesting emerging technique, such as illustrated in the following paper.

Traditional DMM are commonly restricted for underpinning, limitations being mainly related to the capacity of the machine to pass existing foundation structures as reinforced slabs or footings, the reduced working spaces and the possible low headroom conditions. **Melentijevic et al. (2013)** present a case history of underpinning of an existing floor slab in an industrial building using DMM. The soil-cement columns were installed with the new Springsol® tool. After the realization of a contact grouting between the slab and the soil, the slab and the contact grouting layer are cored. The spreadable Springsol® tool is then introduced into the gap. Finally, its blades are opened and the soil-cement column is executed until the predetermined depth. The conception is supported by numerical modeling and QA/QC aspects of the project are related to the testing of core and wet grab samples.

4.2 *Use of stabilized dredged material for construction*

As previously discussed in Chu et al. (2009), dredging and land reclamation have increasingly become important parts of construction activities that involve heavily geotechnical knowledge. If dredging provides low cost construction material, it is sometimes necessary to resort to additional GI methods in order to obtain a product meeting the design requirements. The following paper illustrates how GI and dredging are complementary construction processes.

Loh et al. (2013) present considerations in the design and construction of a containment bund made of modified geotextile tubes (M-GT) filled with cement-mixed soil. In the port of Singapore, dredged soil mixed with cement was used as in-fill material in the M-GT's and as the core of a large geotextile containment bund, as illustrated in Fig. 7. Field instrumentation and monitoring were carried out with the help of strain measurements, hydrographic survey, inclinometers and extensometers during and after the construction to verify the design and the performance of the system.

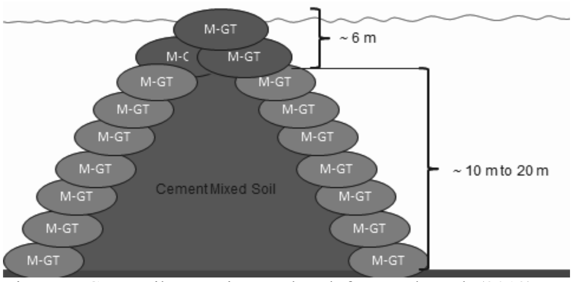

Figure 7. Geotextile containment bund, from Loh et al. (2013)

4.3 *Recent advances in the jet grouting applications*

If special devices have been developed in the past to measure the diameter of the jet grout columns executed in situ, considerable effort should be made in the understanding of the physical processes governing this parameter. **Bzówka et al. (2013)** analyze excavated jet grout columns. The experimental results are used to model the bearing capacity of the columns by means of the Z-soil software. Indeed, although the jet grout columns have been realized in compacted medium sand underlain by stiff clay, almost all columns had an irregular shape influencing its bearing capacity.

In the grouting applications, the bleed capacity is another indicator of grout effectiveness, since it is representative of the volume of voids filled by cement. The grout's water-to-cement ratio (W/C) and the maximum cement grain size (d_{max}) are two important parameters controlling the cement grout bleed capacity. **Pantazopoulos et al. (2013)** provide some insights on the effect of grout bleed capacity on the mechanical properties of ordinary and microfine cement grouted sands, in conjunction with the effect of the W/C ratio. They demonstrate that the distinction between stable and unstable grouts (see EN 12715) may not be an indicator of grout effectiveness since similar effects may be produced by both stable and unstable grouts: e.g. same coefficients of permeability were obtained for a bleed capacity ranging from 5 (stable) to 30 % (unstable suspension). Bleed capacity correlates very well with some grouted sand properties (i.e. unconfined compression strength and cohesion) and not at all with other properties (i.e. internal friction angle and damping ratio).

5 EARTH REINFORCEMENT

5.1 *Geosynthetics*

Centrifuge tests have been performed by **Bo et al. (2013)** in order to study the reinforcement of low plastic brown weathered shale with polypropylene fibers for the construction of an embankment. Vertical and horizontal displacements deduced from the centrifuge tests have been compared with those obtained from FEM analyses. Both approaches demonstrate the contribution of the fibers on the stability.

In a similar way, **Tabarsa and Hajiesmaeilian (2013)** have studied the influence of sand encapsulated non-woven geotextile (sandwich technique) on the stability of clay embankment. Using FLAC 2D Finite Difference model, the authors highlight the efficiency of the method with regard to the geotextile-reinforced and the unreinforced embankments.

5.2 *Vegetation methods*

A significant element in the reclamation of landfills is the reinforcement and biological stabilization of the slopes which can be very sensitive to surface erosion. According to **Koda and Osinski (2013)**, landfill stability improvement activities can be divided in two phases: the first one consists in the technical reclamation of the landfill and the second one is the biological restoration of the vegetation cover. For both phases, the authors argue it is possible to use recyclable materials such as fly ash or sewerage sludge. They discuss the improvement of slope stability of a solid waste disposal with the help of this approach. On the one side, fly ashes can be considered as impermeable and present good compaction properties. Mixed with cohesive soil, it could be therefore used for the capping of the waste disposal. On the other side, the sewage sludge protects the seeds from erosion and excessive drying. Moreover the sewerage sludge presents a high nutrition content supporting the development of the vegetation cover. Unfortunately, no information is given in the paper concerning the installation procedures of the fly ashes and sewerage sludge and how the influence of vegetation can be introduced in the stability calculations.

6 CONCLUSIONS

In the present General Report, 47 papers of the Technical Session on GI of the XVIII ICSMGE are reviewed. It can be noted that 40% of these papers deal with Deep Mixing and soil stabilization, proving the huge interest in these techniques. Similar percentage was already observed in the Proceedings of the TC211 IS-GI 2012 (Denies and Huybrechts, 2012) but this is not surprising, as these methods constitute outstanding and cost-effective sustainable construction processes.

Finally, beyond the choice of the GI solution, the necessity of monitoring was also highlighted by several authors of this Technical Session. For example, **van der Stoel et al. (2013)** discuss a well-documented case history concerning the realization of two deep excavations in the courtyards of a historical building in Amsterdam. Based on 2D FEM calculations, an extensive monitoring program has been proposed and performed (including levelling point measurements, inclinometers and the use of a permanent webcam). Thanks to this monitoring process the consequences of two important accidents during the execution of the excavations could be limited as much as possible. Most important was that the time delay remained very small. The authors conclude that the costs of the meticulous and proactive monitoring were minor in comparison with the potential costs of a delayed opening of the hotel.

If ground improvement is really become an efficient and controllable cost-effective alternative to classical foundation technique, measure still remains treasure.

7 ACKNOWLEDGEMENTS

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