TC211 General Report of the XIX ICSMGE: Ground Improvement works

Rapport général du CT 211 de la XIX CIMSG – Travaux d'amélioration des sols

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ABSTRACT: The TC211 General Report highlights the significant amount of 55 papers of the Technical Sessions of the XIX ICSMGE dedicated to Ground Improvement works. 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 Sessions. 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 official TC211 classification proposed by Chu et al. (2009). The present General Report deals with several aspects of GI works: execution processes, 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.

RÉSUMÉ : Le présent rapport général du CT 211 met en évidence les contributions significatives des articles des sessions « amélioration des sols » de la 19ème 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 des sessions techniques. Ce rapport discute des derniers développements et recherches dans le domaine des travaux d'amélioration des sols. Les différentes techniques sont classées selon la 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.

1 INTRODUCTION

Ground improvement (GI) is one of the major topics in geotechnical engineering. The large number of delivered papers (55) and the organization of the four Technical Sessions within the framework of the XIX ICSMGE illustrate that very well. Ground improvement has become a fast growing discipline in civil engineering as it allow the construction on soft, weak and compressible soils with a cost reduction in comparison with conventional foundation techniques. During the last decades the importance of the ground improvement market has enormously increased. This development was translated in many technical papers published in journals and conference proceedings. It is not possible to mention all. A lot of references are given on the TC211 website (www.tc211.be). As a result of the large number of GI methods available on the market, TC211 adopts a classification system as shown in Table 1 of the State-of-the Art Report of Chu et al. (2009) with the following categories (and main methods):

A. GI without admixtures in non-cohesive soils or fill materials (Dynamic compaction, vibrocompaction…)
B. GI without admixtures in cohesive soils (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 soil mixing, jet grouting…)
E. Earth reinforcement in fill and in cut (Geosynthetics or MSE walls, ground anchors, soil nails…)

In the following sections, the papers of the Sessions of the XIX ICSMGE dedicated to GI works will be reviewed according to this classification (Chu et al. 2009 – available on www.tc211.be).

2 CATEGORY A. GI WORKS WITHOUT ADMIXTURES IN NON COHESIVE SOILS OR FILL MATERIALS

Within the framework of the XIX ICSMGE, 6 papers are dedicated to GI works without admixture in non-cohesive soils or fill materials (CAT. A). The 6 papers describe a different compaction technique. All papers include results from trials or projects.

The paper of **Pistrol et al.** describes the results of a large scale field test, in a gravel pit near Vienna, investigating the use of continuous compaction control (CCC) for oscillating rollers. The use of the compaction response, measured by the acceleration of the drum, was until recent mainly limited to vibratory rollers with the eccentric weights positioned on the axis of the roller (oscillating rollers have two eccentric weight axes placed away from the drum center). The acceleration of the oscillating drum can be described by an infinity symbol in a horizontal and vertical acceleration plot, see Fig. 1 (from Pistrol et al.).

During compaction both the horizontal and vertical acceleration increases, creating the surface area within the eight-shape, as Pistrol et al. call it (see Fig. 1). A mechanical model was defined to investigate the correlation between the soil stiffness and the formation/size of the eight-shape. During compaction the eight-shape continuously changes and the last point of the measurement of the shape does not necessarily coincide with the first point. Pistrol et al. were able to solve this challenge by creating an algorithm in order to approximate the area within the shape with satisfactory accuracy leading to a surface area or a CCC value in [m^2/s^4] for the oscillating drum.

CCC results are shown in the paper for 1, 2, 4 and 8 passes and show the effect of a mattress buried at 15cm and 55cm on the CCC value. After each pass on the trial area a dynamic plate load test was performed on a single spot. The results of the spot test were compared to the mean CCC values of the pass. The Dynamic deformation modulus correspond very well with the CCC value. However, it also shows that a calibration is required for each soil type. The authors provide a complete paper regarding the use of execution monitoring data for a real time control of the compaction.

The paper of **Nagy et al.** gives a first insight into a research performed in order to understand the underlying processes arising in the subsoil during vibrocompaction process. In their research, a lot of accelerometers were positioned on the vibrator and on the soil surface near the compaction location.

The paper written by **Gupta et al.** provides information about a project performed in Greater Noida India. The project described is a university site presenting 8 to 12 m of loose sand layers, susceptible to liquefaction. The specific area is about 2000 m² and required 8 m of ground improvement works. Dynamic Compaction in a 4 m grid was used to compact the subsoil. The paper shows before and after SPT graphs together with an NCEER analysis. In Gupta et al., it is stated that the general formula, depth of influence = $0.5\sqrt{(Weight*Height)}$, was used to determine the effort of the compaction. Although no remark was made in the paper, it seems that the subsoil conditions were not taken into account. This is most likely the main reason for the limited depth of influence of the compaction. The large compaction effect is limited to a depth of about 4 m, which coincides with the ground water level, see Fig. 2. It might have been that a large part of the energy was reflected by the water table, limiting the actual depth of influence. There is still large improvement visible below the water table to about 6 m below the surface.

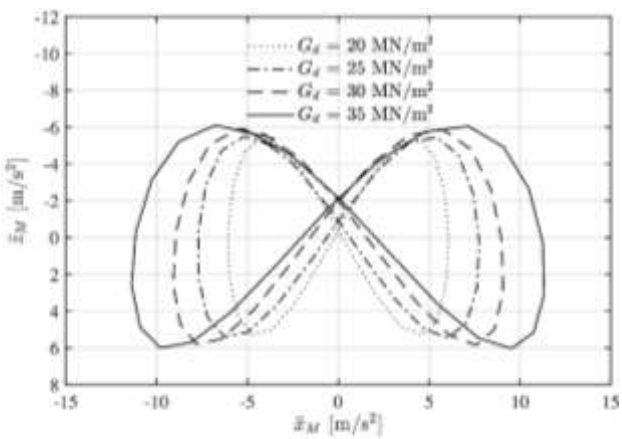

Figure 1. Theoretical shape of the accelerations during compaction (Pistrol et al. ICSMGE 2017)

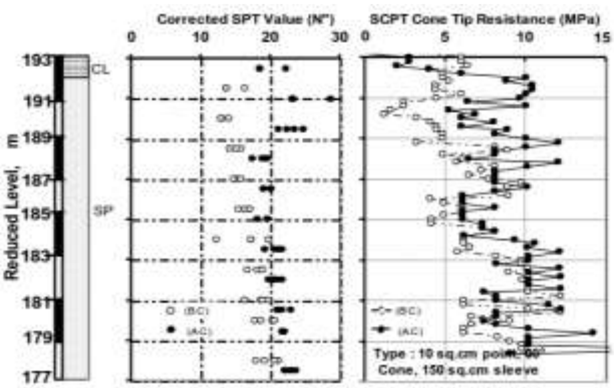

Figure 2. SPT and SCPT before (BC) and after compaction (AC) (Gupta et al. ICSMGE 2017)

Remarkable is however that the improvement is gradually changing into more or less fixed increase in the SPT values between before and after compaction between about 6 meters and 15 meters depth. This does not correspond to normal practice result where the efficiency of the dynamic compaction should decrease with depth.

Tarawneh and Hakam have provided a short project paper about the use of a 9 ton Rapid Impact Compaction for the compaction of a housing estate in Dubai. Unfortunately the paper provides limited information about the soil conditions of the site. It is therefore difficult to fully understand the compaction effort and the compaction results other than the cone resistance for the 4 to 5 m thick section of sand to be compacted. It is difficult to assess the improvement in q_c in relation to the actual soil conditions and mainly fine contents of the soil. As a result, the results of the compaction seem to be low compared to other results of RIC compaction. A large section of the paper focuses on the compaction technique and the choice of the compaction method.

The paper written by **Minaev** shows the results of a theoretical study supported by field tests for the use of an alternative firing method of explosives in the compaction of sand. Theoretical and practical results are provided to support the use of consecutive firing of the charges in adjacent holes in order to prevent the occurrence of the "dead zone" with no liquefaction in the center of the space between two charges. Graphical results of the model are presented to show the theoretical base. Based on the writer theoretical research, a field trial was executed with simultaneous firing of 16 adjacent holes and consecutive firing of 64 holes in series of 16 holes. The consecutive firing was performed with time intervals between explosions varying from 3 to 5 minutes in four phases such that never an adjacent location was detonated during a phase. The conclusion that the consecutive firing method, next to the theory, provides better results in practice, is based on settlement measurements (~35cm for the simultaneous firing over ~40cm for the consecutive firing). The paper also provides the geotechnical properties after compaction. These show very good improvements of the soil with, up to now, more than 10 million m³ of sand improved by the method.

Massarch et al. provide a paper about a project where resonance compaction was applied in eight steel caissons of 13 x 26 m built for the bridge over the Sundsvall in Sweden. The paper provides a lot of information about the system and the project. The resonance compaction was applied in a soil replacement of 8 to 10 m thickness inside cover dams at water depths of up to 14 m. On top of the soil replacement, the bridge foundation was made without piles. Densification was achieved using vibrator mounted on the top of a double Y-shaped light weight probe. The system was vibrated at the resonance frequency of the vibrator-probe-soil system to achieve the most optimal compaction induced from the vertical vibrations. It is described that compaction depends on the penetration speed of the probe. With a minimal requirement of q_c = 10 MPa, the limit was set at 1 m per minute penetration. The final results show very good densification especially after the third phase of compaction with q_c values up to 25 MPa.

3 CATEGORY B. GI WORKS WITHOUT ADMIXTURES IN COHESIVE SOILS

There are 7 articles included in this section. Four papers discuss the salient aspects related to the application of vacuum consolidation (Liu et al., Rujikiatkamjorn and Indraratna, Zhong et al. and Sun et al.) while 2 articles focus on the application of vertical drains to mitigate the adverse effects of earthquakes (Nanaka & Yamada and Rollins & Oakes). Finally, Lee, Tan, Lam and Bok report a project wherein pumping wells were installed to increase the flow rate of discharged water for the large area of a construction site.

Liu et al. propose the modification of the conventional vacuum consolidation process to improve soft soil underwater. Figure 3 presents the construction of a cofferdam constructed with sand cushions to prevent the fluctuation of tidal prior to the installation of vertical drains. A case study at Tianjin Port (China) demonstrated the efficiency of the system through monitoring data including settlements and lateral displacements. The application improved the stability of the slope via inward lateral displacement.

The authors **Rujikiatkamjorn and Indraratna** present a dimensionless parameter to distinguish the relative performance of the improved foundations for vacuum combined surcharge loading, even if the shape of the time settlement curves and the degree of consolidation are similar. The consolidation data obtained from Port of Brisbane (Australia) were used to evaluate the performance of soil consolidation using vertical drains and vacuum combined surcharge preloading. The normalized parameters are determined based on drain length, drain spacing, clay thickness and fill surcharge height. After normalizing by the factor, the areas where a vacuum was applied performed better than the non-vacuum areas, see Fig. 4.

Zhong et al. present an analytical model for radial consolidation capturing the large strain condition and the non-linear soil properties variation during soil consolidation. Case studies at Tianjin Port (China) and Suvarnabhumi Airport (Thailand) were used to validate the model, see Fig. 5. At the sites, the application of vacuum and surcharge loading facilitated by vertical drains was used. Traditional unit cell model based on constant coefficient of consolidation can provide acceptable accuracy to predict the settlement and excess pore pressure. However, for very large deformation, the proposed model that captures the nonlinear compressibility and permeability, non-Darcian flow, and large-strain geometry becomes necessary.

Due to the low shear strength at the surface of dredged clay, **Sun et al.** investigate the application of vacuum preloading via short vertical drains to increase this shear strength.

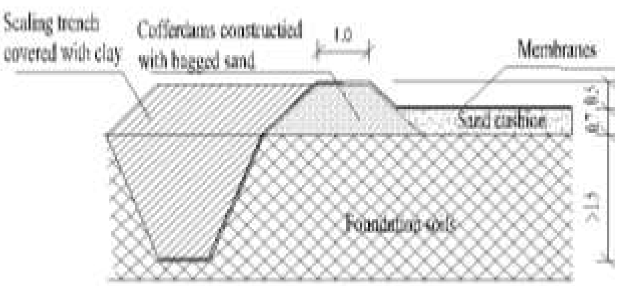

Figure 3. Relationship among the temporary cofferdams, sand cush ion and sealing trench (Liu et al. ICSMGE 2017)

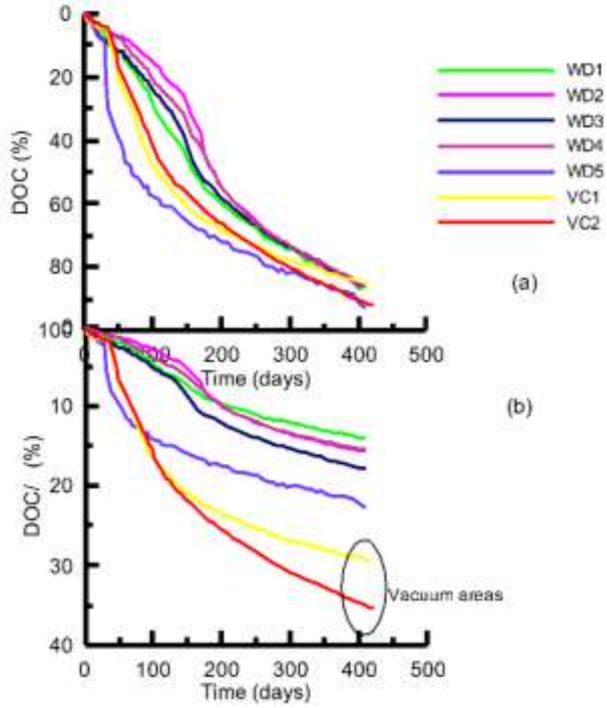

Figure 4. Degree of consolidation (a) before normalizing and (b) after normalizing (Rujikiatkamjorn and Indraratna ICSMGE 2017)

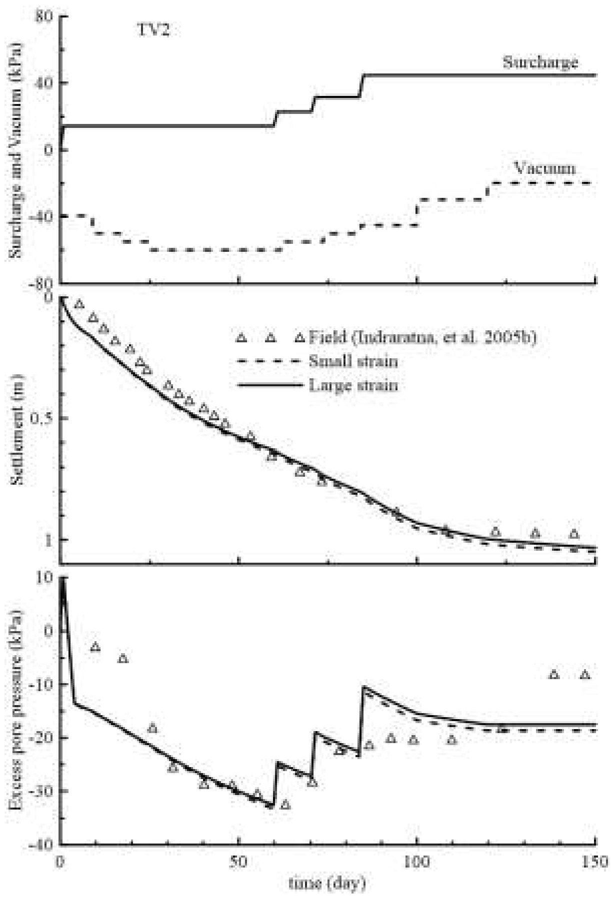

Figure 5. Model validation at Suvarnabhumi Airport (Zhong et al. ICSMGE 2017)

In this study, vertical drains were installed with different drain spacings i.e. 0.4 m and 0.6 m. It is shown that the shorter drain spacing is more effective. The undrained shear strengths and the degree of consolidation of the soil after 2 months were more than 26 kPa and 92%, respectively, satisfying the requirements of the working platform.

Nonaka and Yamada introduce the simulation of vertical drains using macro-element method under dynamic condition. This technique incorporates the coupled finite element analysis with the water absorption and discharge functions of drains into individual elements. Two and three dimensional analyses were performed under earthquake conditions. It is shown that the application of the macro-element method improves calculation efficiency and dramatically reduces calculation times.

Lee, Tan, Lam and Bok present the design of construction process of ground improvement using surcharge fill and vertical drains at Batu Kawan, Seberang Perai, Penang (Malaysia). They describe the subsoil condition of soft alluvium deposit and the conceptual design of vertical drains. The smear zone characteristics including smear zone extent and the permeability ration were $d_s/d_w = 4$ and $k_h/k_s = 2$, respectively. The calculated settlements, based on combined consolidation theory by Terzaghi and Barron equations, are in agreement with the observations. At this site, pumping wells were installed to increase the flow rate of discharged water for the large area of construction site.

As illustrated in Fig. 6, **Rollins and Oakes** performed a physical model using a 6 m high laminar shear box to investigate the efficiency of vertical drains in mitigating liquefaction induced pore pressure and displacements. The experiment consists in the application of 15 sinusoidal cycles with peak accelerations ranging between 0.05g and 0.20g. As a result, the soil with drains could resist liquefaction with an increase in the number of cycles. The rate of pore pressure dissipation was significantly increased with drains and excess pore pressure ratios typically dropped below 0.2 within a few seconds after the end of shaking.

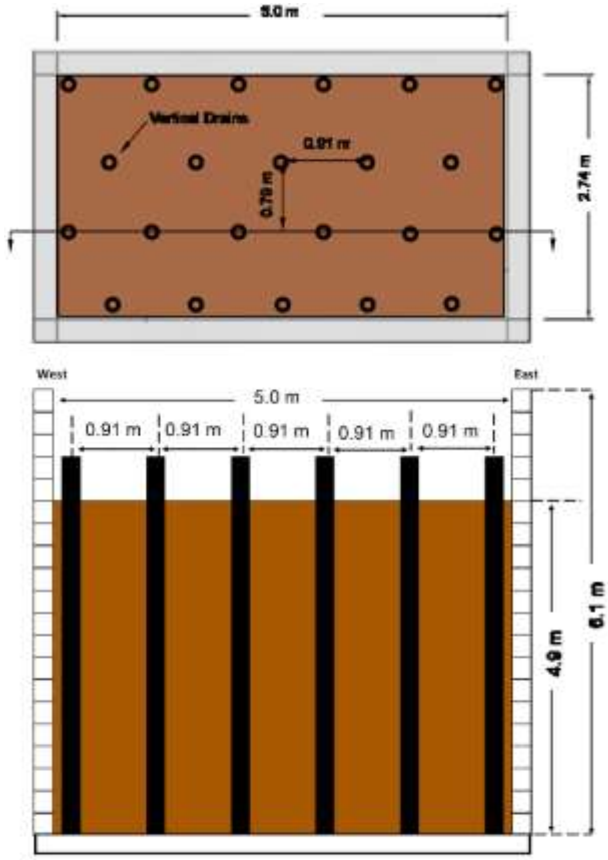

Figure 6. Plan and profile of laminar shear box with vertical drains (Rollins and Oakes ICSMGE 2017)

4. CATEGORY C. GI WORKS WITH ADMIXTURES OR INCLUSIONS

Ground improvement works with admixtures or inclusions are addressed by twenty-three articles. Among those articles, five deal with ground improvement with admixtures. Two papers are dedicated to recent ground improvement techniques: biogas desaturation for liquefaction mitigation (Wu et al.) and bio-cementation for soil stabilization (Cheng and Shahin). Two other papers focus on specific aspects of bacterial treatments: calcium carbonate ($CaCO_3$) bonds produced under the presence and metabolism of a soil bacterium are analysed through micro-computed tomography (**Terzis and Laloui**) and the impact of bacterial biopolymer formation on soil properties is evaluated from a series of laboratory tests (**Kwon et al.**). **Dong et al.** concentrate on the behavior of soft clay stabilized with Saccaromyces cerevisiae, a species of yeast. The authors study its influence on the elastic properties of cement stabilized clays. Finally, eighteen articles are devoted to ground improvement works with inclusions. Flexible inclusions (encased or non-encased stone columns and dynamic replacement pillars) and rigid inclusions (concrete) are discussed either on the base of numerical modeling or through case histories.

4 .1 *Ground improvement with admixtures*

Cheng and Shahin compare the evolution of the mechanical properties of a uniform silica sand treated using either bio-cementation or Ordinary Portland Cement (OPC). Monitored results are the unconfined compressive strength (UCS) and the permeability. Bio-cementation is made possible using Microbial Induced Carbonate Precipitation (MICP). This emerging technique employs ureolytic bacteria to hydrolyze urea in the presence of calcium ions to form calcium carbonate crystals, which act as a cementing agent that binds the soil grains together, resulting in an increase of the soil strength and stiffness. The results indicate that bio-cementation is an effective soil stabilization technique in improving soil strength, with higher achieved UCS values and more limited impact on the permeability than those of OPC-treated soil.

Wu et al. analyse the effectiveness of biogas desaturation for liquefaction mitigation using model tests. Biogas desaturation method consists in producing uniformly into soils very tiny gas bubbles in order to make fully saturated sand slightly unsaturated. Gas bubbles are generated into the soil by denitrification which is a microbial process of nitrate reduction that ultimately produce nitrogen through a series of intermediate steps. Denitrifying bacteria can be isolated from various sources, for example, waste water, soils, sludges and meadows. Denitrification method works well under hydrostatic conditions. When there is groundwater flow, the tiny gas bubbles in sand may not be stable. One method to maintain the long term stability of the generated gas bubbles in sand is bioclogging induced through a Microbial Induced Calcite Precipitation (MICP). Effectiveness of bioclogging is analysed and described in the paper under different flow conditions: hydrostatic, upward flow and downward flow. Permeability tests have highlighted that the use of a low percentage of calcite crystals produced through MICP in sand forms a barrier and reduces the mobility of gas bubbles. A series of shaking table tests was conducted to investigate the seismic response of biogas desaturated sand. Results show that the liquefaction occurs only in fully saturated loose sand under an acceleration of $a = 1.5\ m/s^2$. Liquefaction does not happen when the sand sample is desaturated by the biogas desaturation method to a degree of saturation of 90 percent, as shown in Fig. 7. The pore pressure ratio in biogas desaturated sand is only one tenth of that in fully saturated sand. As a result, the combination of biogas desaturation with bioclogging of the gas bubbles is therefore effective to mitigate sand liquefaction.

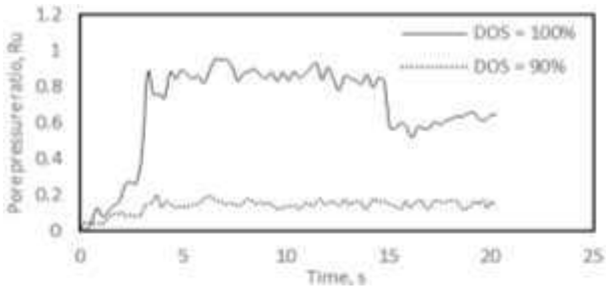

Figure 7: Change of pore water pressure during vibrations (Wu et al. ICSMGE 2017)

4.2 *Ground improvement with inclusions: numerical modeling*

4.2.1 *Flexible inclusions*

Al-Ani and Wanatowski propose a new analytical method completed with numerical modeling to assess the performance of floating stone columns under applied external loads. The critical stone column length is defined and corresponds to the column length where the entire embankment or foundation load pass through the stone column (no load is transferred to the soil). The effectiveness of floating stone columns is investigated by using a relative settlement reduction ratio (RSR) defined as:

$$RSR = \frac{s_0 - s}{s_0} \qquad (1)$$

where s_0 refers to the total settlement at the surface without ground improvement and s refers to the total settlement at the surface of the soft soil improved by stone columns.

A numerical parametric study was performed to validate the analytical approach and to analyze the sensitivity of several parameters: the column length, the column spacing, the thickness of soft soil and the applied loads.

Ramadan et al. perform a parametric numerical analysis (including 59 cases) in order to study the behavior of a footing on soft clayey soil reinforced by a group of floating stone columns. The developed model proved to be capable of predicting the bearing capacity, the settlement and the lateral displacements of these columns under given soil, load and geometry conditions of the group.

Miranda et al. study the effectiveness of stone columns encased with geotextiles in extremely soft soils (s_u<15 kPa), where efficiency of traditional stone columns is low due to insufficient lateral support. Laboratory tests consisting in drained triaxial tests on encased and non-encased samples of gravel have been performed to study the influence of the encasement on the behavior of stone columns. Results of the laboratory tests are compared with numerical simulations, see Fig. 8. Significant improvement evaluated by the ratio of the axial stress increment in the encased and the non-encased samples is highlighted at high axial strain for low confining pressures (maximum ratio is 9.5 at 17% axial strain for a confining pressure of 25 kPa).

4.2.2 *Rigid inclusions*

Racinais et al. insist on the absolute necessity to calibrate the rigid inclusion / soil interaction in numerical models in order to obtain realistic predictions. The method consists in simulating a static load test on a single rigid inclusion and in adjusting the numerical parameters in order to match the numerical results with either in-situ full-scale plate load test or the empirical curves developed by Roger Frank and Zhao in 1982. These curves are proved to be reliable. Their formulation requires the use of the pressuremeter parameters.

Nguyen, Khabbaz, Fatahi and Hsi present the results of a numerical investigation on the effects of the rigid inclusion installation sequence on the already installed columns.

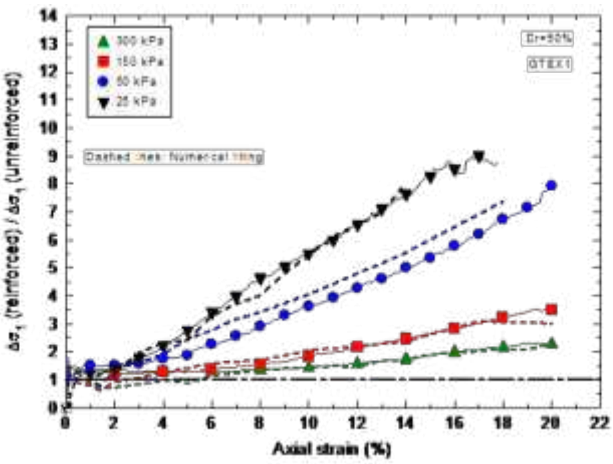

Figure 8: Ratio of axial stress increment (reinforced/unreinforced samples) (Miranda et al. ICSMGE 2017)

Concrete rigid inclusions using a soil displacement auger installed in fully-saturated soft clay are considered in this analysis. In those conditions, the numerical results highlight the need to select an appropriate sequence in order to limit the effects on previously installed columns.

Houda et al. analyze the behavior of the Load Transfer Platform (LTP) under low frequency cyclic surface loading (representing the case of filling and emptying of reservoirs, loading and unloading of storage areas) based on experimental data obtained on a 1g laboratory small scale model and based on numerical models. Tests and models have been performed with or without considering a slab at the top of the LTP. Results mainly focus on the variation of the load efficiency at the rigid inclusion head with the number of cycles, see Fig. 9. The load efficiency expresses the proportion of the total load which is transmitted to the rigid inclusion head. Experimental and numerical results are in a good agreement for the case "without slab". Differences appear in the case "with slab" due to simplifications in the numerical model.

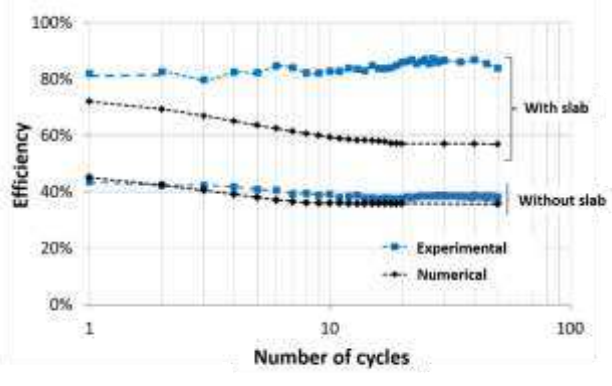

Figure 9: Evolution of the load efficiency with the number of cycles (Houda et al. ICSMGE 2017)

4.3 *Ground improvement with inclusions: case histories*

4.3.1 *Flexible inclusions*

Selvaraju et al. discuss the performance of stone columns under steel storage tanks of diameter up to 89 m and height of 20 m built in a big refinery in Vietnam. Stone columns are installed in a 5-6 m thick loose to dense sandy soil followed by a 8-9 m thick soft to firm clay. The objective of the stone columns is to reduce the settlement to allowable values as a function of the size of the tanks. Tank settlement predictions and hydrotest measurements are compared. Maximum edge settlement measured during the hydrotest reaches 160 mm and is lower than the predicted value of 280 mm. The difference may be explained by the short duration of the hydrotest (3 days) which has not allowed the full consolidation. Anyway, the overall trend of the tank edge settlement observed during the hydrotest is well in agreement with the predictions. Stone columns proved thus to be an attractive alternative solution to classical pile design concept.

Callejas and Luna present the design, the construction and the monitoring of an engine warehouse built in the Genosa power plant in Guatemala over soft soil reinforced by stone columns. The soil conditions consist in interbedded, not consolidated and poorly drained layers of sands and silts, and to a lesser extent in gravels and clays. Stone columns have been designed for settlement purpose and liquefaction mitigation. Settlement monitoring was installed and followed during 1 000 days. During this period, an earthquake of 7.4 magnitude occurred (7th November, 2012). Settlement observed after the earthquake are relatively small (4 mm), no damages were observed due to his event highlighting the effectiveness of stone columns for liquefaction mitigation.

Detert et al. describe the reinforcement of landfill and peat layers by geosynthetic encased granular columns under a high bridge approach embankment (up to 7.0 m) for a new highway in Germany. The high-strength tubular geotextile encasement provides controlled radial confinement and enables reducing settlement and increasing stability. Settlement of the embankment was monitored during 5 years. The largest part of the settlement occurs with the installation of the embankment (15 cm). Then, under constant load, the settlement increases only by 3.5 cm during the next 17 months. No creep settlement occurs after. An additional function was also assigned to the columns: to reduce the lateral pressure of soft soil in depth on the adjacent piles of the bridge abutment. It has been achieved by increasing the area ratio just behind the bridge abutment on piles. Monitoring of the total horizontal stress at different depths has confirmed the lateral pressure relief.

Vincent et al. describe dynamic replacement works performed in Darwin Harbour in Australia for the Ichthys LNG development. The dynamic replacement pillar is a large diameter soil reinforcement column, with a diameter of 2 to 3m, which is formed through a succession of tamping (25 t weight pounder, 10 to 20 m falling height) and back-filling sequences. Dynamic replacement was selected to treat mangrove muds (s_u from 0 to 12 kPa) over 3 to 5 m in order to achieve required bearing capacity and stability and to limit settlement to acceptable levels. The monitoring results during the two years following completion of the works have demonstrated the efficiency of the concept. This method created environment and economic benefits because the excavation and replacement of polluted materials were avoided.

Beuße et al. also describe dynamic replacement works performed in Germany for a large factory but their analysis focuses on the comparison between the Pressuremeter Test (PMT) and the Cone Penetration Test (CPT) as quality control. Correlations between the tip resistance q_c (CPT) and the limit pressure p_l (PMT) are established for the different soil types encountered on the site (hydraulic fill, clay, gravel and sand) and are compared with those found in literature. A good agreement is established. The authors also indicate that the PMT reveals to be the most reliable test for quality control of dynamic replacement works at short term. A higher delay (a few weeks) is required for the CPT to capture the increase of the mechanical soil characteristics.

Generally stone or gravel material is used within the framework of the vibro replacement method. Nevertheless, sand or recycled aggregates may be applied as well for economic reasons. **Wehr and Wecke** present such a development conducted in Germany. A specially designed vibro sand column hopper has been developed to ensure a good efficiency of the process. The GI results obtained with this device were compared with those obtained with a standard skip used on the same site. Furthermore, within the framework of this study, another system was tested in order to install pure fly ash columns. As a conclusion of this study, the authors affirm that various recycled aggregates can be used for the realization of vibro columns: like crushed concrete, quarry waste, building debris, crushed bricks, glass sand and fly ash. However, adequate internal friction angles and moduli have to be taken into account in the geotechnical design and QA/QC process has to be foreseen to verify the in-situ quality of the produced columns.

The aim of the study of **Ben Salem et al.** was to assess the effectiveness of the stone column technique to mitigate liquefaction by considering densification effect. Twenty four cases studies, where SPT and CPT tests have been performed before and after stone columns reinforcement, were used in this view. The results show that the consideration of the densification effect improves the assessment of liquefaction potential of reinforced soil by stone columns.

4.3.2 *Rigid inclusions*

Shatzer et al. present a comparison of available methods for the purpose of estimating the rigid inclusion shaft resistance in clays with actual shaft resistance values estimated from monitored static load tests on isolated rigid inclusions. In clays, the λ method proposed by Vijayvergiya and Focht (1972) appears to provide the best prediction of shaft side resistance and skin-friction capacity. The estimation of the shaft resistance by this method is highly sensitive to accurate selection of the soil properties (undrained shear strength and unit weight). Thus, the authors insist on the importance of obtaining good laboratory test data for design of rigid inclusion projects which mainly rely on skin-friction capacity.

Thomas et al. describe the project of a huge clinker storage dome in Colombia, see Fig. 10. The dome is 36 m high and based on a concrete ring beam of 60 m in diameter. This configuration leads to very high loads imposed at the surface level, up to 570 kPa at the center of the dome in operation. The foundation ground is composed of a succession of silty sand, sandy silt and silty clay layers overlaying a claystone base.

The use of soil reinforcement by rigid inclusions with a narrow spacing allowed to reduce the settlements to values compatible with the operational requirements of the clinker storage facility. Maximum absolute settlement is limited to 10 cm at the center of the dome and differential settlement does not exceed 1/500. Rigid inclusion design (diameter, length and spacing) was conducted with the help of a 3D finite element model. In particular, the rigid inclusion spacing was adapted to the load applied.

Figure 10: Picture of the constructed dome (Thomas et al. ICSMGE 2017)

4.4 *Ground improvement with inclusions: analytical approaches*

In their article, **Ter-Martirosyan et al.** analyze the behavior of stone columns used as bearing and drainage elements. The presented solutions include an analytical solution of the interaction problem between the bearing elements, the slab and the surrounding soil. The results of lab and in-situ tests are also presented.

Lee, Kim, Lee, Lee and Jung focus on the current design guidelines for piled embankment in Europe which generally assume a fixed soil arch in circular or spherical shape without specific consideration on the variabilities in material properties and geometric configurations. In their paper, the authors suggest a new design method for the piled embankment including the state-dependent shape of soil arch considering possible variabilities. In addition, experimental data obtained from small-scale model tests were compared with the current and the new proposed methods.

Mirsayapov and Koroleva developed an analytical model to compute the bearing capacity and the deformation of soil foundations reinforced with vertical elements under cyclic loading.

Most of the publications of the CAT. C are dealing with GI works with inclusions. Flexible inclusions (11 papers) are more represented than rigid inclusions (7 papers). Half of the articles dedicated to GI works with inclusions are case histories. The other half mainly focuses on numerical modeling. The main interest of this approach lies in the possibility of carrying out parametric studies for the purpose of analyzing the sensitivity of different parameters.

5. CATEGORY D. GI WORKS WITH GROUTING TYPE ADMIXTURES

There are 14 articles included in this section. 7 papers deal with material properties (admixtures) and 7 papers consider tests, practical issues or numerical calculations.

Knopp and Moormann present the influence of the binder content and type of binder on ettringite swelling in the treatment of sulfate-containing soils. If soils with natural sulfate content were treated with calcium-based binders, the binder may react under certain conditions with sulfate ions to cause the mineral ettringite. Swelling tests show volume increase, caused by the mineral reaction which may cause uplift damage. The research contributes to the choice of binder and the development of a practical test specification.

Kaneda and Imai present a method for preventing liquefaction by using grid-form deep mixing walls on a liquefiable soil layer below a non-liquefiable layer. A non-liquefaction layer above the liquefaction layer tends to prevent liquefaction. Centrifuge model tests and numerical simulations confirmed that the increase in pore water pressure was prevented when the non-liquefiable soil thickness was increased. This indicates that a wider grid interval can be set than usual when non-liquefiable soil is considered. Considering the effect of the presence of a non-liquefiable soil layer above the liquefiable soil layer and the installation of grid-form deep mixing walls, both can prevent liquefaction and mitigate the surface settlement.

Dang et al. present an experimental study on engineering behavior of lime and bagasse fibre reinforced expansive soils. A series of laboratory tests evaluate the influences of bagasse fibres and hydrated lime addition on the engineering properties and swelling behavior of stabilized expansive soils. Results of CBR-, swell potential- and one-dimensional consolidation tests after various curing time are discussed in detail. The results show that this type of soil reinforcement leads to a significant increase in compressive strength and bearing capacity of expansive soil, whilst swell potential and compressibility decreased with increasing fibre content.

Forsman et al. present a paper on global mass stabilization and quality control methods. The applicability of sounding and sampling methods for quality assurance (QA) are discussed as well as the soil parameters that can be determined using these methods. The column penetrometer (method illustrated in the standard EN 14679-2005) and the vane penetrometer have been used in Finland over three decades and a good statistical correlations have been reached between the sounding results and the shear strength of stabilized soil. However, these methods are not always available for the in-situ characterization of mass stabilization sites in all regions. In those circumstances, other QA methods are needed. Some experiences and opinions about the suitability of several other QA methods for the control of mass stabilized soil are presented in this paper. As a conclusion of the authors, the suitability of these investigation methods have to be considered site by site if the experience of the stakeholders with QA for mass stabilization is limited. Moreover, because of the heterogeneity of mass stabilized soil, a statistical approach should be implemented for the assessment of the stabilized soil parameters.

Nguyen, Takeyama and Kitazume present a study on failure mechanisms of deep mixing columns reinforced by a shallow mixing layer. As illustrated in Fig. 11, centrifugal model tests were carried out in order to investigate the failure pattern of the deep mixing columns beneath an embankment slope. The columns are fixed and reinforced by a cement stabilized shallow layer in order to increase the horizontal resistance of the group of columns. In addition, simple calculations based on the equilibrium method were conducted to evaluate the failure patterns obtained from the centrifugal model tests. The effect of a shallow layer on the failure pattern of the columns is also discussed.

Ishii and Kitazume present an assessment of injection pressure of plastic grout for the improvement of a boulder mound. This method, where a plastic grout is injected into the ground, is on the rise in Japan. In presence of boulders, the voids between the boulders are much larger than those of e.g. sandy soils and conventional cement grout or chemical grout are not applicable because the grout settles due to gravity and disperses due to surrounding water before it solidifies. Plastic grout is commonly used so that voids between boulders can be filled up and solidification can be achieved without settlement and dispersion of the grouting material. In this study, small-scale and full-scale injection tests are conducted to evaluate the performance of the plastic grout and an analytical method is proposed that enables quantitative prediction of time-dependent injection pressure based on the boulder size and strength of the plastic grout.

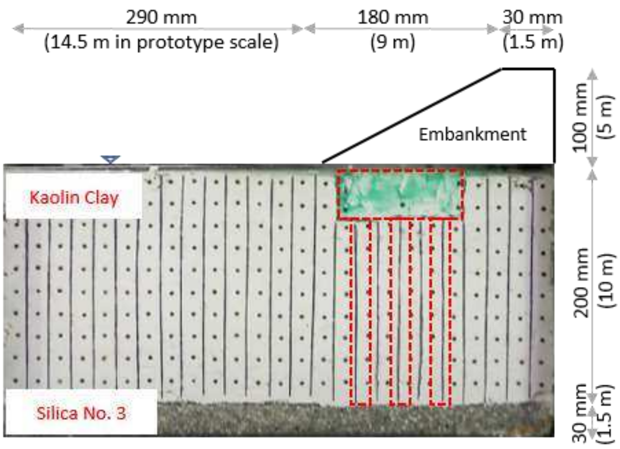

Figure 11: Model ground of centrifuge model tests (Nguyen et al. ICSMGE 2017)

Inazumi and Sekitani present the development of an impermeable coating treatment for reutilization of contaminated soils and solid wastes. This study evaluates the basic properties, such as the elution of heavy metals and water permeability for treated soils, by laboratory experiments. The technology coats solid wastes and soils by a particle unit with the impermeable material containing water-absorbing polymers. Each particle of soils is coated with impermeable materials uniformly. Furthermore, the treated soils are expected to improve their water interception performance.

Hamada and Honda present a case history of a 10-story base-isolated building constructed on liquefiable sandy soil. A piled raft solution, combined with grid-form cement deep mixing walls, was employed. Field monitoring of the settlement and the load sharing was performed for about seven years since the beginning of the construction and the recorded data during the 2011 Tohoku Earthquake, arisen one month after the end of the construction, show that this combined solution effectively works in liquefiable and soft soils.

Khomyakov et al. present some modern methods of strengthening of soft soil in the bases of constructions on soft soil and unstable soil which occupies more than 30% of the territory of Kazakhstan. Experiences of strengthening of loessial collapsible soils by mixed chemical and mechanical methods are given in this article.

Boulanger et al. focus on the mitigation of liquefaction effects for a dam using soil-cement grids. Numerical simulations and centrifugal tests are used to model an embankment dam installed on a liquefiable foundation layer treated with soil-cement walls. The model was shaken with a scaled earthquake, causing liquefaction in the loose sandy layer. Crack detectors monitored the soil-cement walls shearing though their full length. The two-dimensional nonlinear dynamic simulations were compared with the test results, showing capabilities and limitations of the two-dimensional simulations of soil-cement grid reinforcement systems. Finally, the implications for practice are discussed.

Hanson et al. focus on the compaction and durability characteristics of polymer modified soils. An extensive laboratory test program was undertaken to enhance the understanding of the engineering significance of polymer amendment. Engineering properties determined throughout the test program included dry unit weight-water content relationships through compaction tests and durability through freeze-thaw and wet-dry tests. The addition of polymer significantly affected the optimum water content and to a lesser extent the maximum dry unit weight. The amount of polymer required to modify the engineering properties was directly related to specific surface of the soils.

Pandrea and Lambert present the effects of a grid formed into the ground with shear walls made by deep soil mixing or jet grouting in a seismic area. The shear walls are constituted of soil-mix trenches and act like a confined shear box which significantly increases shear stiffness against horizontal stress. The design principle is based on the reduction of soil distortion. The results show a new dynamic response at the surface resulting in a reduction of seismic stresses inside the building.

Lim et al present the development of controlled low strength material (CLSM) using self-cementitious fly ash. In order to find the optimum mixing condition satisfying flow consistency and UCS, the CLSM specimens were prepared under various mixing conditions, including varying aggregate types and fractions. Additionally, the prepared specimens were evaluated through scanning electron microscope and X-ray diffraction. The results of this study demonstrate that the USC and the workability increase with increasing the fraction.

As proposed by Jian Chu in Brussels during the IS-GI 2012, it is maybe necessary to add a new subcategory of method in the CAT. D: the bio-grouting methods (D7) same if the subcategory C7 of Chu et al. (2009) already consider the microbial methods. In the present conference, **Kim and Park** concentrate on the applicability of biogrouting in sandy ground. The biogrouting process, considered in their study, is a combination of the injection technology for soft ground treatment with the MICP method (previously discussed in Section 4.1). Based on lab test results, it was confirmed that the UCS of sand stabilized with biogrouting material, OPC and micro cement was increased by more than 30% in comparison with the UCS of OPC stabilized sand.

6. CATEGORY E. EARTH REINFORCEMENT IN FILL AND IN CUT

In their paper, **Pham et al.** concentrate on an experimental study of the strain mechanisms developed inside geosynthetic-reinforced granular platforms located above cavities. New highways or railway line constructions sometimes cross areas of potential collapses due to the presence of underground cavities. Among solutions, the use of geosynthetic-reinforced embankments increases. In this study, a new lab device has been developed to simulate a cavity by both processes and for various ratios between the height of the platform and the diameter of the cavity. Tests performed on three different soils and one geosynthetic reinforcement have notably allowed to define the shape of the soil area affected by the sinkhole.

In their article, **Corbet and Cazzuffi** give an overview of the numerous recent developments conducted by the CEN/TC189 and ISO/TC221 dedicated to the establishment of European and International standards for geosynthetic products.

7. PAPERS DEALING WITH SEVERAL CATERGORIES AND METHODS

In his article, **Holtz** gives an overview of the historical developments related to GI works. Beginning with the old and well-known methods (e.g. soil replacement by excavation, displacement by blasting, chemical grouting…), the author then focuses on recent developments in soil improvement (Pre-fabricated vertical drains PVD, lime columns, dynamic compaction and pile supported embankments). The paper describes the early history of these relatively newer techniques using the results of some case studies in which the author was directly involved.

In his paper, **Ben Braiek** discusses on the concept and the applicability of different methods: dynamic compaction, dynamic replacement and vibro-replacement techniques. The author provides a chart for the selection of one of these techniques as a function of the nature of the soil.

Koçak et al. report a current case history in Turkmenistan. That concerns a nearshore seaport project with a total gross area of 115 hectares. A very soft clayey layer was encountered during the soil investigation with a depth varying between 6 and 10 m from the seabed level. To improve the soft clay layer, a PVD solution with a preloading was planned including a monitoring of the settlement. To enhance the parameters of the reclaimed sand, the Rapid Impact Compaction method was introduced. For both GI solutions an optimization of the processes was established on the basis of test areas.

8. CONCLUSIONS

The present General Report reviews 55 papers of the Technical Sessions on GI works of the XIX ICSMGE. These papers illustrate a lot of possibilities of the GI methods currently available on the market and highlight the importance of a suited in-situ monitoring within the framework of real field cases.