DRAFT ISSMGE TC211 Working document – Control of vibrocompaction works – State-of-the Art Report and Code of Good Practice

1. Context of the State-of-the Art Report

Due to the expansion needs of our societies and to the world population growth, it becomes more and more important to allow the construction of new structures (buildings, houses, fills, embankments…) on soft soils presenting poor mechanical characteristics (soft, weak, alluvial, compressible soils, mud, sludge, saturated sand with high liquefaction potential…). This is the reason why Ground Improvement (GI) methods are increasingly applied all over the world. One recognized technique in order to improve granular soils and fills is the vibrocompaction method (also called vibroflotation method).

As reported in *Chu et al. (2009)*, in the last few years, vibrocompaction (or vibroflotation) has been used for a number of mega projects in the world, for example the Changi East Reclamation Project in Singapore (*Bo et al. 2005*) and the Palm Projects in Dubai (*Wehr, 2007*). The vibrocompaction method was pioneered by John Keller in 1936 following the invention of the depth vibrator. The more recent techniques are reported by *Mitchell (1981)*, *Welsh et al. (1987)*, *Massarsch (1991)*, *Massarsch and Fellenius (2005), Raju and Sondermann (2005)* and *Kirsch and Kirsch (2016)*.

During the last mandatory period 2013-2017, the ISSMGE TC211, the international Technical Committee of the ISSMGE dedicated to the ground improvement works, introduced as principal theme for its activities the "Design, Quality Control and Quality Assurance for ground improvement works".

Within the framework of its activities, the ISSMGE TC211 particularly focused on the design and QA/QC of the ground improvement works performed by the vibrocompaction process resulting in the present summary/State-of-the Art Report and overview of the Codes of Good Practice.

2. Execution, design and control of the vibrocompaction method

In Europe, the execution of the vibrocompaction process falls under the auspices of the European standard **EN 14731** Execution of special geotechnical works - Ground treatment by deep vibration.

This European Standard is applicable to the planning, execution, testing and monitoring of ground treatment by deep vibration achieved by depth vibrators and compaction probes.

In this standard, the deep vibratory compaction is defined as a type of ground treatment by deep vibration in which the main purpose is to densify the soil. The treatment is applicable to many granular soils and normally results in increased strength and stiffness, reduced permeability and reduced susceptibility to liquefaction.

The Section 7 of the EN 14731 describes the considerations related to design of ground treatment by deep vibrations.

As prescribed in this section, the following shall be defined in the design of the ground treatment:

- **technical objective of the treatment** (e.g. increased bearing capacity, reduced settlement; reduced liquefaction potential, reduced potential for collapse settlement on wetting or reduced permeability);
- **required geotechnical properties of the treated ground** (e.g. shear strength, stiffness, or permeability);
- **criteria on which treatment depth, spacing and extent are decided**;
- target performance and **the way in which treatment is to be assessed in terms of measurable parameters**;
- where excavation subsequent to treatment takes place, proposals for recompaction if necessary.

As specified in the EN 14731, due to the nature of ground, variations are to be expected even after treatment and this should be taken into consideration[†].

Where deep vibratory compaction is not intended to compact the surface layer, rollers or tampers should be used to compact this layer. Alternatively, compaction can be executed from a level above final foundation level.

Concerning the design verification, it is clearly specified in the EN 14731 that suitable means of verifying that the required treatment objectives have been achieved should be identified prior to commencement of ground treatment, in terms of the results of defined tests.

The Section 9.2 of the EN 14731 describes the testing of ground treatment by deep vibrations.

The primary purpose of testing is to assess the performance of the treatment. The choice of test method should be influenced by the objective of ground treatment. In some situations, the time that has elapsed between treatment and testing will have a significant effect on the test result. The parameters to be monitored, the test locations, the frequency of testing and criteria for acceptance shall be defined prior to execution. Testing shall be appropriate for the amount of treatment, variability of ground conditions, type of foundation, depth of influence of foundation loading and any other relevant factors.

For the control, the following in situ tests may be carried out:

- cone penetration tests (CPT and CPTU) carried out to provide a continuous record of penetration resistance, friction ratio and, for CPTU, induced pore pressure;
- dilatometer tests (DMT) carried out to determine deformation moduli;
- dynamic probing (DP) carried out to provide a record of the penetration resistance;
- pressuremeter tests (PMT) carried out to determine deformation moduli and/or limit pressures;
- standard penetration tests (SPT) carried out to determine the penetration resistance.

In some situations, the execution of large-scale load tests can be envisaged.

3. Cone Penetration Tests for the post-verification of the ground treatment by deep vibrations/vibrocompaction/vibroflotation

As, in practice, the realization of CPT's is generally used to judge the suitability of the vibrocompaction method (see Figure 1), a post verification of the ground treatment by an in situ test campaign consisting in the realization of a determinate amount of CPT's seems to be the most common verification test method encountered on the international market (cf. *Massarsch, 1991* and *Wehr, 2007*).

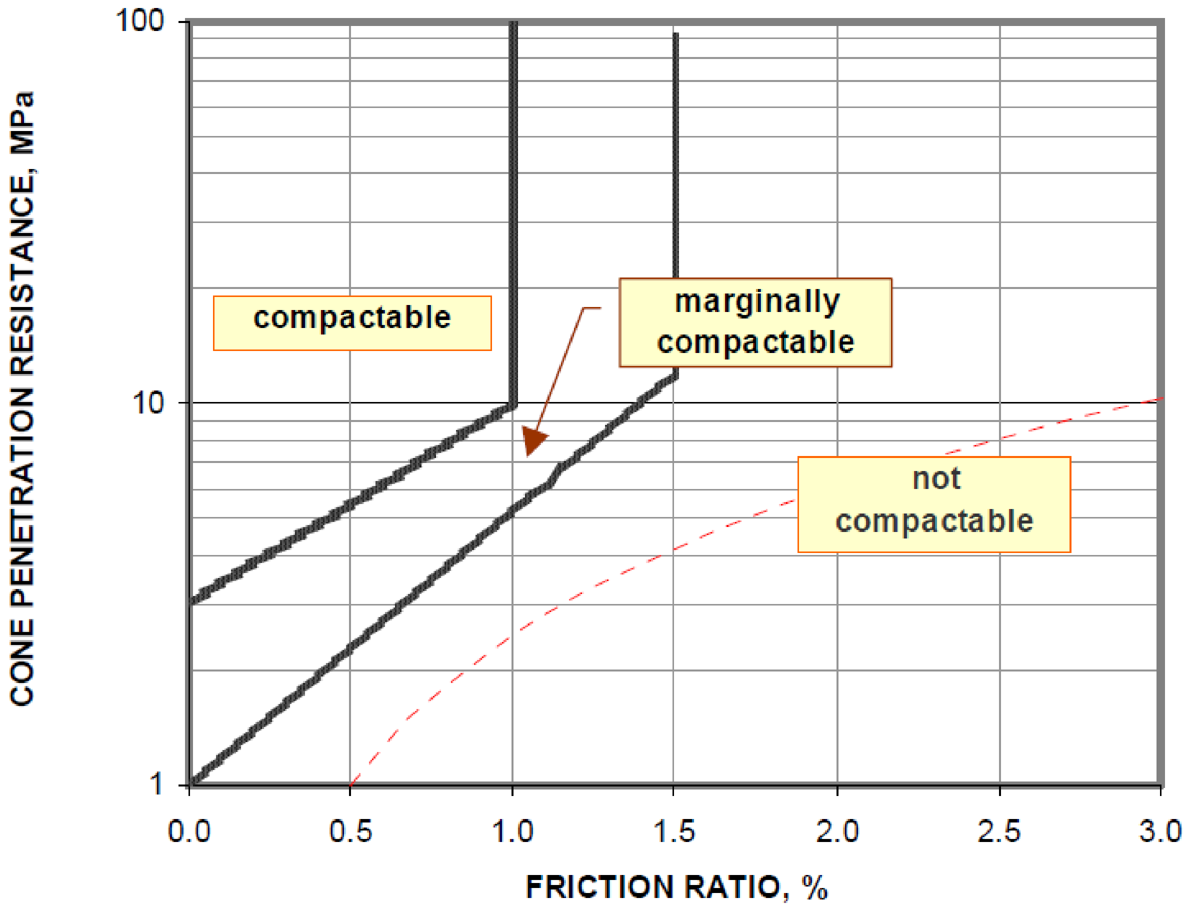

Figure 1 - Soil classification for deep compaction based on CPT data (after Massarsch, 1991)

Massarsch and Fellenius (2002) underlined the fact that the CPT is an efficient and operator-independent tool for assessing the characteristics of sandy coarse-grained soils. It has become the most widely used field investigation method for compaction projects, gradually replacing the SPT, which previously was the dominant in-situ testing method for this purpose.

The way the results of the CPT's are interpreted before and after completion of the ground improvement works has still to be defined.

Within the framework of the XVI European Conference on Soil Mechanics and Geotechnical Engineering, held in September 2015 in Edinburgh, the ISSMGE TC211 organized a Workshop dedicated to the ground improvement works and titled: *"Progress in QC/QA for GROUND IMPROVEMENT works".*

In-situ testing plays certainly a major role in the QA/QC of GI works. The synergy with the **ISSMGE TC 102 In situ testing** was evident and the TC 211 had therefore invited Professor Antonio Viana da Fonseca (University of Porto), the Chairman of the TC 102 to make a special presentation during this workshop: *"Quality Control of Ground Improvement Works by In Situ testing"*

A major part of his presentation was dedicated to the post verification of ground treatment by deep vibration. As highlighted in his presentation and discussed during the Workshop with the TC211 members, an efficient way to interpret the CPT results performed after completion of the works is to follow the computational method explained and reported in the **CUR/CIRIA HYDRAULIC FILL MANUAL** (van t'Hoff and van der Kolff, 2012).

CUR/CIRIA Hydraulic Fill Manual method for the post-verification of ground treatment by deep vibration using averaged CPT data

As underlined in the **CUR/CIRIA HYDRAULIC FILL MANUAL**, in-situ tests, such as the CPT may be carried out to verify the required quality of the ground treatment by deep vibrations. **Quality control may be based on a weighted profile of the cone resistances measured in CPT's executed at, for instance, a number of two specified positions within the compaction grid‡** (= ground improvement pattern). Figure 2 shows examples of such locations[1]. **The use of a moving average value (e.g. over a depth of 0.5 to 1.0 m) of the mean cone resistance ensures a rational evaluation of the compaction results as it averages the effect of incidental thin horizons of less compacted fill in the quality assessment.** The actual positions of the CPT's for verification of the achieved improvement should preferably be specified in the Contract documents in order to avoid discussions during the execution works. The evaluation report regarding the compaction efforts shall also include the unprocessed data of the CPT's for reference. It is further important to accurately localize the actual coordinates of the pre- and post-compaction test locations.

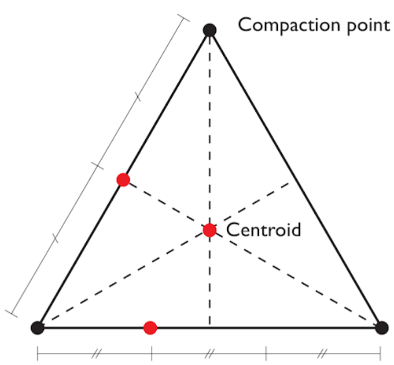

Figure 2 – Example of possible post-vibroflotation test locations (coloured dots) related to a triangular compaction grid (black dots) – from CUR/CIRIA Hydraulic Fill Manual (2012)

[1] In line with the requirements of the EN 14731 – cf. note† on page 2

Figure 3 presents an example of filtered average values of the cone resistance and sleeve friction before and after vibratory compaction of a hydraulic fill installed for the construction of the new Hong Kong Airport (from *Massarsch and Fellenius, 2002*). In order to obtain interpretable CPT values and to perform the comparison "pre/post compaction", the authors used the **arithmetic average of the values of the different CPT's** (four precompaction and seven postcompaction CPT's), **filtered to smooth out the peaks and troughs of the records**. The filtering is made by a running geometric average over a 0.5 m record length (= moving average procedure).

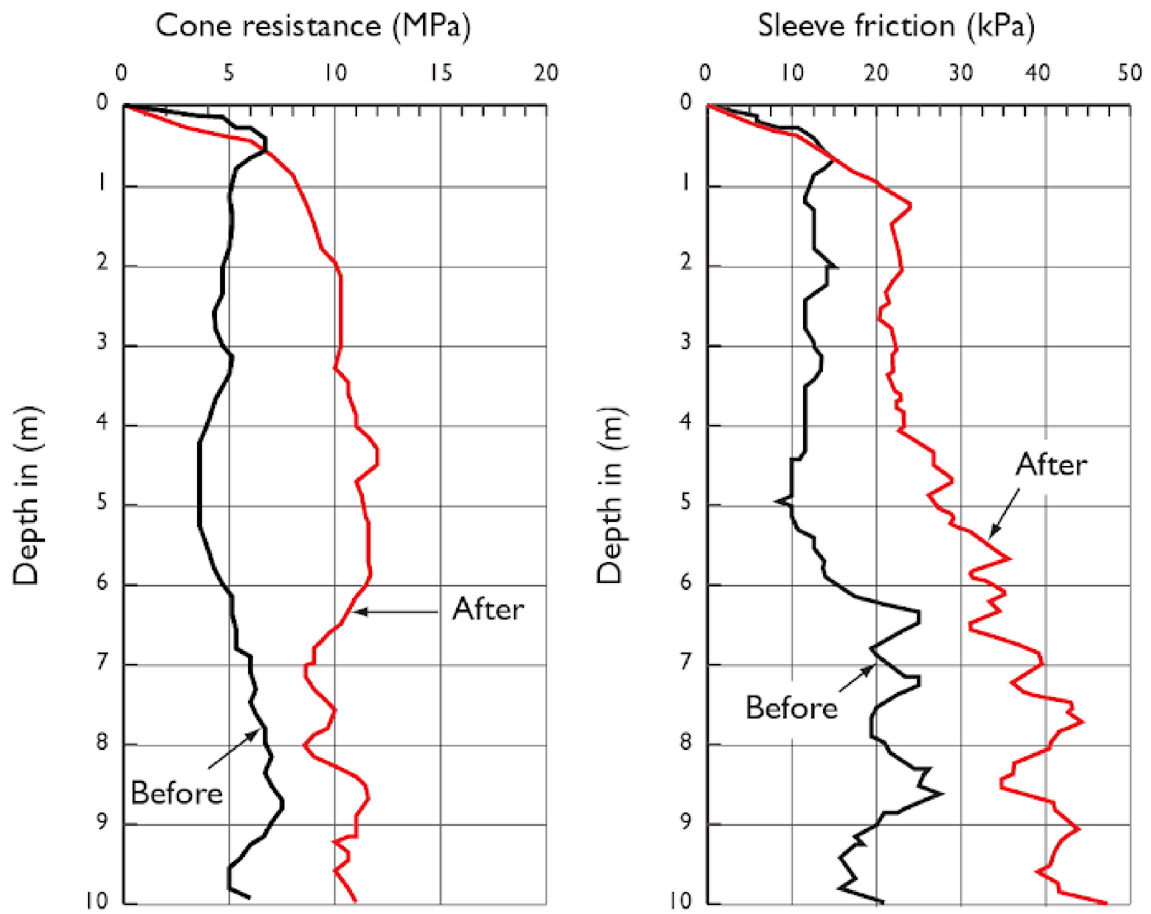

Figure 3 – Example of filtered average values of the cone resistance and sleeve friction before and after vibratory compaction of a hydraulic fill (from Massarsch and Fellenius, 2002)

More information on the interpretation of the results of the CPT's performed after completion of the tests can be found in *Massarsch and Fellenius (2002)* notably on the topic of the cone stress values adjusted with respect to the mean effective stress.

Massarsch and Fellenius (2002) also used the averaged (arithmetic mean) and filtered (moving averaged) values of the CPT results for the purpose of conducting settlement calculations. Soil Moduli and modulus numbers are determined from the averaged filtered postcompaction CPT data.

It is to note that the question of the use of the filtered CPT values (obtained from a moving average computational approach) was already discussed within the framework of the TC211 (former TC17) Workshop 2007 at the 14th ECSMGE of Madrid. Jimmy Wehr, at that time from the Keller company, had presented the ground treatment works by deep vibrations for the realization of the Palm Island in Dubay. Within the framework of this large construction project, Jimmy Wehr had explained that the extreme CPT peak values had been averaged over 1 m to obtain interpretable results allowing the reception of the works. According to his experience, thin layers of cohesive soil with interbedded layers generally result in a large scatter of the cone resistance profile and it is necessary to average the results in order to obtain relevant CPT profile allowing the post-verification of the ground treatment by deep vibration/vibrocompaction.

4. Conclusions

Considering the presentations and the experiences of Jimmy Wehr (2007) and Viana de Fonseca (2015) and the scientific article of Massarsch and Fellenius (2002), it seems that the moving average procedure described in the **CUR/CIRIA HYDRAULIC FILL MANUAL (2012)** is well-suited for the post-verification of the ground treatment by vibrocompaction/vibroflotation/deep vibrations by means of the CPT's. Massarsch and Fellenius (2002) use the arithmetic average of the values of the precompaction and postcompaction CPT's, filtered to smooth out the peaks and troughs of the records (with a moving average procedure) in order to verify the effect of the vibrocompaction works.

As the question of post-control of ground treatment by deep vibrations by means of averaged values of the CPT results seems to come back regularly within the framework of the ISSMGE TC211 activities, we recently decide to create a working group (a task force) which will shortly work on that matter and which will include the big actors of the vibrocompaction market. Keller Holding, Menard and Bauer will probably be part of that working group accompanied by the TC211 board and some experts in this field of the geotechnical engineering.

Indeed, as a result of the experience gained on big construction sites these last fifteen years and considering the "lessons learned from", it seems that "standard practices" are currently observed on the market for the control and the acceptance of the vibrocompaction works (see Table 1). The new TC211 working group will first concentrate on these "standard practices" to analyze their legitimacy/validity in order to control the result of vibrocompaction works. Based on the future discussion inside the task force, it is the purpose to propose a harmonized international consensus for the QA/QC of vibrocompaction works to the practice. This QA/QC methodology will therefore be in agreement with the State-of-the Art of the practice and it will respect the experience of the different actors of the market: customers, designers, general and GI contractors and technical control bureaus.

Table 1 - Proposed "Standard practices" for the QA/QC of vibrocompaction works to be studied by the "TC211 Working Group on Vibrocompaction"

Based on the existing data of the scientific/technical literature and on the field experience: - QA/QC of vibrocompaction works based on the analysis of the **averaged values** of two CPT's per triangular compaction grid[2]. The control is thus based on the average values of the CPT-curves (resulting in a weighted CPT curve) and not considering the local CPT data of one CPT profile. It has still to be determined if the averaged values consist in the arithmetic mean of the results of the different CPT's or consist in an area weighted average regarding the location of the analyzed CPT's (see Table 2). - Acceptance criteria never based on only one CPT profile as the ground treatment cannot be considered as uniform even after treatment and the CPT is a local method of control.[3][4][5] - Use of a moving average value (e.g. over a depth of 0.5 to 1 m) of the mean/weighted cone resistance ensuring a rational evaluation of the compaction as proposed in the CUR/CIRIA Manual. - Comparison of the **averaged** (resulting of the averaging of the two CPT curves) **filtered** (moving averaged) CPT profile with the required q_c-curve (where q_c is the cone resistance) <u>allowing</u> that parts of the <u>averaged</u> <u>filtered</u> CPT profile are under the required q_c-curve (i.e. present smaller cone values than required) <u>on the strict conditions that:</u> (1) the cumulated length of these parts under the required q_c-curve is smaller than 10 to 15% of the treated height AND, (2) that the global design criteria (in terms of bearing capacity, settlement limitation, liquefaction mitigation…) are reached considering the computed <u>averaged</u> <u>filtered</u> CPT profiles. - QA/QC requirements, specified in the contract / job specifications, have to consider the compaction suitability of the soil to be treated. This suitability can be analyzed on the basis of CPT results (see Figure 1 for example) or based on the soil type and the particle size distribution (see, for example, *Kirsch and Kirsch, 2016*). Soil layers presenting not compactable characteristics should be removed from the analysis and from the QA/QC verification, possibly including transition zones as defined in *Robertson and Cabal (2015)* in the interpretation. - If necessary, the shell content has to be considered in the QA/QC analysis.[6]

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[2] In line with the requirements of the CUR/CIRIA Manual - cf. note‡ on page 4

[3] In line with the requirements of the EN 14731 – cf. note† on page 2

[4] As explained in Kirsch and Kirsch (2016), with increasing radial distance from the vibrator, the ground vibrations are attenuated by the forces acting between the soil particles. As a result, there is an attenuation of the postcompaction density as a function of the radial distance from the vibrator automatically resulting in a heterogeneous soil state after treatment (independently from the initial precompaction soil conditions).

[5] As reported in Massarsch and Fellenius (2002) for the case of the hydraulic fill installed for the construction of the new Hong Kong airport (CPT results illustrated in Figure 3), in spite of the relative uniform compaction procedure, significant variations in cone stress and sleeve friction can be noted for the postcompaction CPT's.

[6] As reported in *Kirsch and Kirsch (2016)*, various researchers have found that even relatively small percentages of shell debris (10%-20%) (Vesic, 1965; Cudmani, 2001) in silica sand have considerable influences on the CPT point resistance at the same density.[…]. Wehr (2005) presented a shell correlation factor f_s as a function of the relative density D_r for Dubai sand (carbonate content in excess of 90%, $D_{60}/D_{10} = 3$) by which the CPT results measured in the calcareous sand need to be multiplied to arrive at corresponding values for silicate sand.[…]. Accordingly this correlation factor ranges between 1.4 and 1.8 and amounts to 1.64 for a relative density of 60%.

Table 2 – Use of a weighted profile of cone resistances of postcompaction CPT's for the control of the vibrocompaction works

Considering the issue of the QA/QC based on a weighted profile of the cone resistances of the post compaction CPT's, *Kirsch and Kirsch (2016)* reported the control procedure for the ground improvement works performed for the extension of a major shipyard in Singapore. The construction of a large hull shop on Tuas Island for a major shipbuilder required extensive ground improvement works which were carried out in 2013 and 2014 for the foundation of its heavy structures. The structural design was based upon relatively stringent deformation criteria. The postconstruction settlement was generally restricted to only 50 mm with differential settlement along crane rails not to exceed 1 in 1000. An area of 126 000 m² was treated by vibrocompaction to depths between 11 and 26 m. To accomodate the deformation criteria for the various parts of the large hull structure, the postvibrocompaction soil stiffness was specified by the soil consultant in terms of carefully selected, standardized CPT acceptance criteria. Based on five postcompaction CPT results, an <u>area weighted average</u> was calculated which then served as reference curve for a treated representative sand volume to be compared for the acceptance with the specified target curves. In this control methodology, the acceptance is thus based on a weighted profile of the cone resistances of the post compaction CPT's.

REFERENCES

Bo, M.W., Chu, J. & Choa, V. 2005. The Changi East reclamation project in Singapore. Chapter. 9, Ground Improvement Case Histories, B. Indraratna & J. Chu (Eds.), Elsevier: pp. 247-276.

CUR/CIRIA. 2012. Hydraulic Fill Manual. For Dredging and Reclamation Works. CRC Press, Taylor and Francis Group. ISBN 978-0-415-69844-3.

EN 14731. 2005. European standard for the Execution of special geotechnical works – Ground Treatment by deep vibration. CEN/TC 288.

ISSMGE TC211. 2009. State of the Art Report. Construction Processes. SoA Report published within the framework of the 17th International Conference on Soil Mechanics and Geotechnical Engineering. Egypt, October 5-9, 2009. Redacted by Jian Chu, Serge Varaksin, Ulrich Klotz and Patrick Mengé. Available online: www.tc211.be

ISSMGE TC211. 2015. Proceedings of the TC211 Workshop of Edinburgh (XVI ECSMGE 2015) available online: www.tc211.be

Kirsch, K. and Kirsch, F. 2016. Ground Improvement by Deep Vibratory Methods. CRC Press, 2nd Edition.

Massarsch, K.R. 1991 Deep Soil Compaction Using Vibratory Probes, Proceedings of Symposiumon Design, Construction, and Testing of Deep Foundation Improvement: Stone Columns and Related Techniques, Bachus, R.C. Ed. ASTM Special Technical Publication, STP 1089, Philadelphia: pp. 297–319.

Massarsch, K.R., and Fellenius, B.H., 2002. Vibratory compaction of coarse-grained soils. Canadian Geotechnical Journal, 39(3), pp. 695-709.

Massarsch, K.R. & Fellenius, H. 2005. Deep vibratory compaction of granular soils. Chapter 19, In Ground Improvement – Case Histories, B. Indraratna & J. Chu (Eds.), Elsevier, 539-561.

Mitchell, J.K. 1981. Soil improvement: state of the art report. Proceeding of the 10th international conference on soil mechanics and foundation Engineering: pp. 509-565.

Raju, V.R., & Sondermann, W. 2005. Application of the vacuum preloading method in land reclamation and soil improvement projects. Chapter 21, Ground Improvement - Case Histories. B. Indraratna & J. Chu (Eds.), Elsevier, 601-638.

Robertson, P.K. and Cabal, K.L. 2015. Guide to Cone Penetration Testing for Geotechnical Engineering. 6th Edition.

Viana da Fonseca, A. 2015. Quality Control of Ground Improvement Works by In Situ testing. Presentation within the framework of the TC211 Workshop of Edinburgh (XVI ECSMGE 2015). Presentation available online: www.tc211.be

Wehr, J. 2007. Vibro Compaction of reclaimed land, Presentation at the TC 17/TC211 Workshop at 14ECSMGE, Madrid, 27 Sept. Available on demand: nde@bbri.be

Welsh, J.P., Anderson, R.D., Barksdal, R.P., Satyapriya, C.K., Tumay, M.T., & Wahls, H.E. 1987. Densification. In J.P. Welsh (Ed.), Soil Improvement - A Ten Year Update, ASCE Geotechnical Special Publication No. 12: pp. 67-97.